NCFRP

REPORT 31

NATIONAL
COOPERATIVE
FREIGHT
RESEARCH
PROGRAM

Sponsored by the
Office of the Assistant
Secretary for Research
and Technology

Incorporating Truck Analysis into the *Highway Capacity Manual*

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

NATIONAL COOPERATIVE FREIGHT RESEARCH PROGRAM

NCFRP REPORT 31

Incorporating Truck Analysis into the *Highway Capacity Manual*

Richard Dowling
KITTELSON AND ASSOCIATES, INC.
Oakland, CA

George List
Bo Yang
INSTITUTE FOR TRANSPORTATION RESEARCH AND EDUCATION
NORTH CAROLINA STATE UNIVERSITY
Raleigh, NC

Erika Witzke
CAMBRIDGE SYSTEMATICS, INC.
Chicago, IL

Aimee Flannery
WORKING ENERGY ENTERPRISES, LLC
Arlington, VA

Subscriber Categories
Design • Freight Transportation • Planning and Forecasting

Research sponsored by the Office of the Assistant Secretary for Research and Technology

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2014
www.TRB.org

NATIONAL COOPERATIVE FREIGHT RESEARCH PROGRAM

America's freight transportation system makes critical contributions to the nation's economy, security, and quality of life. The freight transportation system in the United States is a complex, decentralized, and dynamic network of private and public entities, involving all modes of transportation—trucking, rail, waterways, air, and pipelines. In recent years, the demand for freight transportation service has been increasing fueled by growth in international trade; however, bottlenecks or congestion points in the system are exposing the inadequacies of current infrastructure and operations to meet the growing demand for freight. Strategic operational and investment decisions by governments at all levels will be necessary to maintain freight system performance, and will in turn require sound technical guidance based on research.

The National Cooperative Freight Research Program (NCFRP) is a cooperative research program sponsored by the Office of the Assistant Secretary for Research and Technology under Grant No. DTOS59-06-G-00039 and administered by the Transportation Research Board (TRB). The program was authorized in 2005 with the passage of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). On September 6, 2006, a contract to begin work was executed between the Research and Innovative Technology Administration, which is now the Office of the Assistant Secretary for Research and Technology, and The National Academies. The NCFRP will carry out applied research on problems facing the freight industry that are not being adequately addressed by existing research programs.

Program guidance is provided by an Oversight Committee comprised of a representative cross section of freight stakeholders appointed by the National Research Council of The National Academies. The NCFRP Oversight Committee meets annually to formulate the research program by identifying the highest priority projects and defining funding levels and expected products. Research problem statements recommending research needs for consideration by the Oversight Committee are solicited annually, but may be submitted to TRB at any time. Each selected project is assigned to a panel, appointed by TRB, which provides technical guidance and counsel throughout the life of the project. Heavy emphasis is placed on including members representing the intended users of the research products.

The NCFRP will produce a series of research reports and other products such as guidebooks for practitioners. Primary emphasis will be placed on disseminating NCFRP results to the intended end-users of the research: freight shippers and carriers, service providers, suppliers, and public officials.

NCFRP REPORT 31

Project NCFRP-41
ISSN 1947-5659
ISBN 978-0-309-28431-8
Library of Congress Control Number 2014946498

NOTICE

The project that is the subject of this report was a part of the National Cooperative Freight Research Program, conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council.

The members of the technical panel selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

The opinions and conclusions expressed or implied in this report are those of the researchers who performed the research and are not necessarily those of the Transportation Research Board, the National Research Council, or the program sponsors.

The Transportation Research Board of the National Academies, the National Research Council, and the sponsors of the National Cooperative Freight Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of the report.

Published reports of the

NATIONAL COOPERATIVE FREIGHT RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet at:

http://www.national-academies.org/trb/bookstore

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. C. D. Mote, Jr., is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Victor J. Dzau is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. C. D. Mote, Jr., are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is one of six major divisions of the National Research Council. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied activities annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

COOPERATIVE RESEARCH PROGRAMS

CRP STAFF FOR NCFRP REPORT 31

NCFRP PROJECT 41 PANEL
Freight Research Projects

AUTHOR ACKNOWLEDGMENTS

The authors would like to acknowledge the contributions of the following people to this project:

- Kent Taylor, NCDOT – Provided WIM data.
- Brian Menyuk, NYSDOT – Facilitated the acquisition of NY-7 freeway data and Hoosick Street data.
- Michael Burke, NYSDOT – Provided the NY-7 freeway data and Hoosick Street data.
- Guillermo Ramos, NYSDOT – Provided the NY-7 freeway data and Hoosick Street data.

In addition, we would like to acknowledge the contributions of the following research team members to this project:

- Dr. Nagui Rouphail – ITRE – Assisted with the HCM testing.
- Dr. Bastian Schroeder – ITRE – Provided simulation support.
- Dr. Senanu Ashiabor – Processed the FHWA freight analysis framework data.
- Dr. Vasin Kiattikomol – Assisted in conducting the signal PCE research.
- Chirag Safi – Assisted in conducting the signal PCE research.
- Dr. Alexander Skabardonis – Conducted the signal PCE research.

FOREWORD

By B. Ray Derr
Staff Officer
Transportation Research Board

This report presents capacity and level-of-service techniques that (1) improve transportation agencies' abilities to plan, design, manage, and operate streets and highways to serve trucks and (2) better evaluate the effects of trucks on other modes of transportation and vice versa. These techniques are being incorporated into the *Highway Capacity Manual,* but will be immediately useful to planners and designers working on projects with significant truck traffic.

In 2009, trucks moved 10.9 billion tons of freight; by 2040, trucks are expected to move 18.4 billion tons of freight (FHWA, *Freight Facts and Figures 2010*). The growth in trucking can be attributed to a number of factors including changes in population and employment; the modal shift of freight to trucks from other modes; and changes in the economy and business practices that affect the freight transportation system. Transportation decisions should facilitate and account for freight flows, but analysts lack the tools needed to evaluate them.

The *Highway Capacity Manual* (HCM) is a fundamental reference for the operational analysis of streets and highways. While the 1950 HCM was focused on automobile traffic, later editions have incorporated research that has been conducted on pedestrians, bicyclists, and transit users. The 2010 HCM, however, largely considers trucks only as they impact other travelers. Incorporation of truck analysis into the HCM will help transportation agencies address the freight and highway needs of their community, region, state, and nation.

In NCFRP Project 41, a research team of Kittelson and Associates (prime), Cambridge Systematics, Working Energy Enterprises, and the Institute for Transportation Research and Education at North Carolina State University took a comprehensive approach to addressing this issue. In addition to a literature review, federal, state, regional, and local agencies were contacted to document the state of the practice. Carriers and shippers were interviewed to determine the critical factors that affect logistical decisions.

Based on the insights from these activities, the research team developed a truck level-of-service framework. This framework was refined through two workshops with a wide variety of public transportation agency staff to ensure that it would be useful in their work, particularly in evaluating the impacts of system improvements on goods movements. The utility of this framework was demonstrated through the development of three case studies.

The research team then collected field data and calibrated simulation models on freeways and arterials. These models were used to develop improved methods of estimating performance measures for trucks and other vehicles. This effort did determine that both the current HCM methodology and the new methodology are not reliable for long, steep grades. Follow-on research to develop a better freeway methodology for these conditions has been funded by the National Cooperative Highway Research Program (NCHRP).

The report includes several recommendations for improvements to the HCM, and these are being considered in NCHRP Project 03-115, which is updating the HCM for expected publication in 2015.

CONTENTS

1 **Section 1** Introduction
1 1.1 Problem Statement
1 1.2 Research Objective and Products
2 1.3 Approach
4 1.4 Relationship to Reliability Research Projects

5 **Section 2** State of Public Agency Practice
5 2.1 Federal Agency Practice
6 2.2 State Agencies
7 2.3 Multi-Regional Agencies
7 2.4 Regional and Local Agencies
9 2.5 Findings from Public Agencies Survey
10 2.6 Conclusions from State of Practice Review

11 **Section 3** Truck Carrier and Shipper Perspectives
11 3.1 Background
12 3.2 Approach and Methodology
14 3.3 Shipper Carrier Surveys
19 3.4 Findings from Shipper Carrier Survey
23 3.5 A Model to Quantify Quality-of-Service Perceptions
27 3.6 Conclusions on Carrier and Shipper Perceptions

28 **Section 4** Literature Review
28 4.1 Critique of the HCM 2010
37 4.2 International Practice
44 4.3 Conclusions of Literature Review

46 **Section 5** Recommended HCM Truck Classification Scheme
47 5.1 Existing National Truck Classification Schemes
52 5.2 Other Classification Schemes
53 5.3 HCM Vehicle Classification
54 5.4 Determinants of Truck Performance in a Traffic Stream
55 5.5 Data Collection Considerations
56 5.6 Trucking/Shipping Industry Perspectives
56 5.7 Recommended NCFRP Project 41 HCM Truck Classification Scheme

59 **Section 6** Truck Level-of-Service Framework
59 6.1 Establishing a Facility's Freight Importance Class
60 6.2 Derivation of LOS Model 1
64 6.3 Derivation of Model 2
67 6.4 Streamlined Utility Model (Model 2)
67 6.5 Logistic Formulation with Truck Friendliness (Model 3)
70 6.6 Reliability and Friendliness (Model 4)

71 6.7 Results of Review by Public Agencies
71 6.8 Recommended Truck LOS Model

72 Section 7 Truck Level-of-Service Case Studies
72 7.1 Study Site 1—California Class I Interstate Freeway
75 7.2 Study Site 2—Virginia Class I Interregional Freeway
77 7.3 Study Site 3—Urban/Rural Highway

81 Section 8 Prediction of Freeway Truck Speeds
81 8.1 Existing HCM Treatment of Trucks on Freeways
81 8.2 Research Objective and Approach
83 8.3 Initial Field Assessment
85 8.4 The Freeway Test Bed
85 8.5 Calibration of Acceleration Profiles
88 8.6 Truck Footprint for VISSIM
88 8.7 VISSIM Simulations and PCE and Speed Model Development
89 8.8 The Speed Prediction Models
94 8.9 Freeway Truck and Automobile Speed Model Case Study
96 8.10 Freeway Truck Travel Time Reliability

99 Section 9 Prediction of Arterial Truck Speeds
99 9.1 Existing Truck Treatment on Arterials in the HCM
102 9.2 Approach
102 9.3 Acceleration Profiles
102 9.4 Midblock Arterial Segment Speed Model Development
103 9.5 The Predictive Procedure for Midblock Arterial Segment Speeds
107 9.6 Arterial Case Study
109 9.7 Truck Speeds through Roundabouts
113 9.8 Arterial Truck Travel Time Reliability

115 Section 10 Predicting the Effect of Trucks on Capacity
115 10.1 The Freeway Truck PCE Models
117 10.2 Arterial Segment Truck PCEs
118 10.3 Creating Composite Trucks for Capacity Analysis
120 10.4 Signalized Intersection Truck PCEs
129 10.5 Roundabout Intersection Truck PCEs

134 Section 11 Conclusions and Recommendations
134 11.1 Conclusions
135 11.2 Recommendations
136 11.3 Recommended HCM Implementation Plan
138 11.4 Applicability of Results to Practice
138 11.5 Recommendations for Further Research

140 References

145 Appendixes A–F

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

SECTION 1

Introduction

National Cooperative Freight Research Program (NCFRP) Project 41 is a 24-month, $500,000 research project to facilitate the incorporation of trucking industry considerations into all planning studies by developing performance measures, level-of-service models, and truck analysis methodologies that can be applied within the *Highway Capacity Manual* framework.

1.1 Problem Statement

In 2009, trucks moved 10.9 billion tons—63% of the estimated 16 billion tons of freight shipped in the United States; by 2040, trucks are expected to move 18.4 billion tons of freight (FHWA, 2010: *Freight Facts and Figures 2010*). The growth in trucking can be attributed to a number of factors including changes in population and employment, the modal shift of freight to trucks from other modes, and changes in the economy and business practices that affect the freight transportation system. Transportation decisions should facilitate and account for freight flows, but analysts lack the tools needed to evaluate them.

State Departments of Transportation (state DOTs) and metropolitan planning organizations (MPOs) currently take into account the importance of trucking to state and local economies through various specialized freight studies and action plans. However, the vast majority of these agencies' planning efforts do not explicitly incorporate trucking industry perspectives and needs when planning and prioritizing general transportation improvements. Freight planning is a parallel, specialized effort of these agencies, not part of their mainstream planning practice. This "separate but equal" approach to truck planning is caused partly by the specialized nature and needs of the trucking industry, but also by the lack of tools for evaluating trucking industry needs when performing conventional planning studies.

The *Highway Capacity Manual* (HCM) is the fundamental reference for the operational analysis of streets and highways. It is one of the fundamental analysis tools used in conventional planning practice, and while it provides several methods for evaluating the impacts of trucks on automobile traffic, it has no methods for evaluating the impacts of facility performance on truck LOS. Incorporation of truck analysis into the HCM will help transportation agencies address the freight and highway needs of their community, region, state, and nation.

1.2 Research Objective and Products

The objective of the research has been to develop improved, nationally accepted capacity and level-of-service techniques suitable for incorporation into the HCM that

- Improve transportation agencies' abilities to plan, design, manage, and operate streets and highways to serve trucks and

- Better evaluate the effects of trucks on other modes of transportation and vice versa.

Techniques are needed for uninterrupted and interrupted flow facilities in both rural and urban conditions.

1.3 Approach

The research proceeded according to the tasks and schedule described below.

Task 0: Amplified Work Plan

The objective of this task was to provide an expanded version of the approved research plan, budget, and schedule in response to comments from the project panel on the draft work plan.

Task 1: Literature Review

The purpose of this task was to analyze, describe, and critique pertinent domestic and international research on the basis of applicability, conclusiveness of findings, and usefulness for the analysis of truck operations on streets and highways.

This task documented how trucks are addressed in the HCM 2010 and identified deficiencies. This task also reviewed the HCM equivalents found in research and used in other countries to identify techniques and material that could be useful additions to truck application of the HCM 2010 (TRB, 2010).

Task 2: DOT and MPO Survey and Interview Data Collection

The purpose of this task was to interview representative state DOT and MPO personnel and other practitioners to

- Determine how the HCM could be appropriately used in the analysis of truck operations on streets and highways (e.g., freight corridors and connectors, rural mountainous freeways and multilane highways, and urban streets).
- Identify deficiencies in the HCM related to truck analysis.
- Identify and describe methods that practitioners have used to successfully adapt the HCM methodologies to meet their needs in analyzing truck traffic.
- Describe how the results of truck analysis should be considered in the planning and prioritization of projects and the performance measurement of the system.

Task 3: Shipper/Carrier Survey and Interview Data Collection

The objective of this task was to identify the critical performance measures that affect trucking industry (shipper/carrier/logistical consultants) perceptions of the operation of streets and highways and to develop information on their perceptions of different levels of highway and street operation for use in developing and calibrating truck level-of-service models.

Task 4: Truck Classification

The aim of this task was to develop a classification scheme for trucks that is consistent with national schemes but suitable for inclusion in the HCM. Performance characteristics (e.g., acceleration, deceleration, weight, length, emissions, and operational constraints) for each class should be described in both laden and unladen states.

Task 5: Conceptual Framework

The purpose of this task was to develop a conceptual framework for analyzing truck operations in the HCM. This task identified and described the specific data collection and analysis efforts needed to develop the framework and methodologies within the framework. This task catalogued the input data that was likely to be needed for the analysis methodologies included in the framework and described sources for that data.

Task 6: Interim Report and Panel Meet

A project interim report was prepared summarizing the work done in Tasks 1 through 5 and presenting an updated work plan for the remaining tasks. The research team met with the NCFRP project oversight panel for the review and approval of the interim report.

Task 7: Execute Data Collection Efforts, Develop Models and Methodologies

Data collection and analysis efforts were conducted during this task to develop the framework and methodologies as identified in Task 5 and approved at the interim meeting.

Task 8: Case Studies and Panel Meet

This task developed case studies demonstrating how the framework and methodologies developed in Task 7 could address typical applications identified in Task 2. The case studies were intended to highlight improved capabilities over existing methods and to advance the adoption and implementation of the NCFRP Project 41 research results by the profession.

Task 9: Supplemental Chapter Development

This task developed a supplemental chapter to the HCM 2010 that fully presents the framework and methodologies. The draft chapter identifies the limitations of these methods as well as any special considerations such as for sensitivity analysis. The chapter provides and discusses the appropriate use of default values. This chapter is intended to be suitable for publication in Volume 4 of the HCM 2010.

Task 10: Computational Engine

A computational engine (software with very basic user interface) was developed to illustrate the application of the truck analysis methodology in a way that was more robust than selected case studies. In addition, the computational engine was developed to expedite the development of the case studies. The computational engines were also intended to promote the development of more commercially oriented software products that would greatly facilitate adoption and application of the NCFRP Project 41 research results by the profession.

Task 11: Public Agency Workshops to Evaluate Methods

This task involved field testing of the draft chapter through workshops with public agency personnel. Public agency participants at the workshops were asked to provide insights and feedback for consideration of the panel and the Highway Capacity Committee. The public agency workshops also had the serendipitous result of making key local agency practitioners aware of the new NCFRP Project 41 methodologies and how to best apply them.

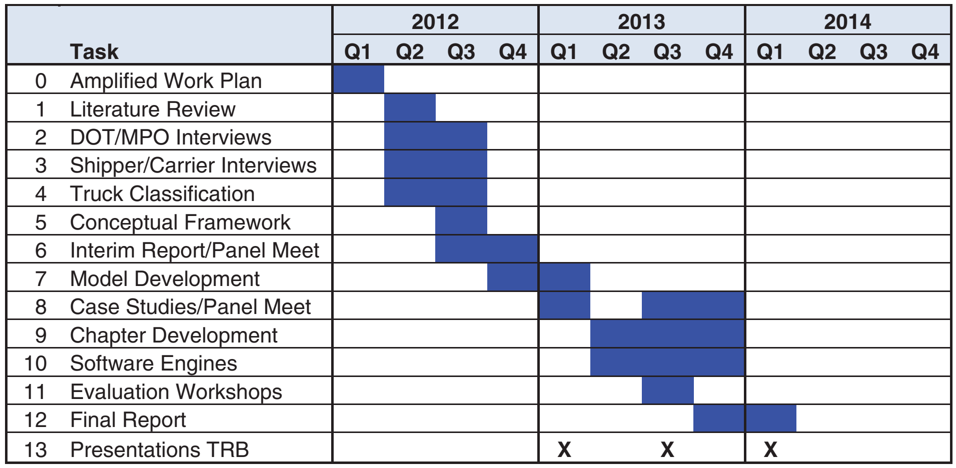
Task 12: Final Report

The purpose of this task was to finalize the draft HCM chapter on truck analysis and to develop a final report that documents the entire research effort including the revised HCM chapter as a stand-alone appendix. The report also describes how the material in that chapter could be incorporated into a future edition of the HCM.

Task 13: Presentations and Webinars

The objective of this task was to keep the TRB Committee on Highway Capacity and Quality of Service (HCQS) and the profession informed of study progress and results so as to facilitate inclusion of the research results in the next edition of the *Highway Capacity Manual.*

Exhibit 1. Planned project time schedule.



Project Time Schedule

The project began April 5, 2012 and was completed by April 4, 2014. The time schedule is presented in Exhibit 1.

1.4 Relationship to Reliability Research Projects

NCFRP Project 41 and SHRP2-L08 reliability research project are intimately related. The reliability performance measures produced by the SHRP2-L08 project are key inputs to the truck level-of-service models for NCFRP Project 41.

SECTION 2

State of Public Agency Practice

This section reviews how public agencies plan for truck freight movement and establishes a context for how public agencies might use a separate level-of-service measure for trucks. Current federal, state, and local practices are reviewed with examples drawn from several state agencies and MPOs.

Freight planning has only recently come to the fore as a significant planning issue, especially for state and local agencies—for example, states and localities now see freight planning as an essential component of economic development. As another example, effects of freight movement on air quality are an increasing concern in non-attainment areas such as the Los Angeles region.

Freight planning is also a national issue. The recent report of the National Surface Transportation Policy and Revenue Study Commission devoted a significant amount of discussion to freight planning issues, including the increasing importance of an efficient goods movement system for the economic health of the United States (*National Surface Transportation Policy and Revenue Study Commission*, n.d.).

2.1 Federal Agency Practice

The U.S. DOT recently announced the creation of a Freight Policy Council that will focus on improving the condition and performance of the national freight network to better ensure the ability of the United States to compete in today's global economy (FHWA, n.d.: *Releases and Speeches*). The formation of the council follows the passage of MAP-21, which calls for the creation of a National Freight Strategic Plan.

2.1.1 Federal Highway Administration

FHWA carries out a number of freight-related functions including the following (FHWA, n.d.: *Freight Management and Operations*):

- Setting truck size and weight standards (FHWA, n.d.: *Truck Size and Weight*);
- Planning, funding, and maintenance for the National Highway System (NHS) (FHWA, n.d.: *National Highway System*). This includes the interstate system and corridors designated by Congress as "high priority corridors";
- Conducting policy studies in support of efficient freight movement; and
- Developing and making accessible information on freight commodity flows.

2.1.2 National Transportation Safety Board

NTSB has an Office of Highway Safety, which includes the following:

- Investigations Division—investigates accidents involving issues with wide ranging safety significance and
- Report Development Division—researches national highway safety issues, develops accident reports, and issues safety recommendations.

2.2 State Agencies

State agencies provide several functions related to freight movement, such as the following:

- Include freight planning as part of statewide transportation planning,
- Establish weigh stations, and
- Set size and weight limits for trucks on the state highway system that is not part of the Interstate Highway System.

An example of a state that provides several functions related to freight movement is California. California performs freight planning research, issues bonds to fund infrastructure improvements on trade corridors (i.e., Trade Corridors Improvement Fund), and produces a goods-movement action plan.

2.2.1 Caltrans Freight Planning Research

The Freight Planning Branch of the California DOT (Caltrans) conducts analyses of freight transportation system performance and future trends, develops freight mobility plans and modal studies, and recommends improvements to goods movement systems and operations through system planning, regional planning, intergovernmental review, participation on multi-state goods movement advisory committees, and other activities.

2.2.2 Trade Corridors Improvement Fund

The Highway Safety, Traffic Reduction, Air Quality, and Port Security Bond Act of 2006—approved by the voters as Proposition 1B in 2006—made $2 billion available for infrastructure improvements along federally designated "Trade Corridors of National Significance" in California or along other corridors within California that have a high volume of freight movement.

The funds were made available to the California Transportation Commission upon appropriation in the annual Budget Bill by the Legislature and subject to such conditions and criteria as the Legislature may provide by statute.

This $2 billion program within Proposition 1B is known as the Trade Corridors Improvement Fund (TCIF). The types of projects considered under this program include highway expansions, grade separations, rail capacity, and port access improvements. In selecting projects, the Goods Movement Action Plan was considered, among other factors.

2.2.3 Goods Movement Action Plan

Caltrans is currently updating its Goods Movement Action Plan (GMAP) under the working title of the "California Freight Mobility Plan." The GMAP was issued in 2005 and 2007 and helped guide project selection for the allocation of funds under the TCIF program.

Like the GMAP, the Freight Mobility Plan will address current conditions, future trends, and major issues in goods movement across all modes and regions of California. Going further than what the GMAP addressed, the Freight Mobility Plan will devote more attention to community impact issues, take a more in-depth look at trucking, and will identify more thoroughly the freight needs of portions of California that did not receive sufficient attention during development of the GMAP. This update will also benefit from important regional freight mobility planning programs that partner agencies have been engaged in and will utilize recent freight industry plans developed by seaports, railroads, and others.

New considerations that have emerged for the Freight Mobility Plan include the following:

- Climate change goals and greenhouse gas emissions,
- New legislative mandates including sustainable communities,
- Adaptation to sea-level rise,
- New trends in international and interstate goods movement,
- Regional differences throughout the state in goods movement and infrastructure,
- How to best obtain substantive input from stakeholders,
- Identifying and evaluating projects and developing criteria to set priorities, and
- Integration with other state plans and programs.

2.3 Multi-Regional Agencies

A number of multi-regional agencies have been created to deal with freight issues that transcend individual regions and states. One example is the Mid-America Freight Coalition (MAFC) which was formerly known as the Mississippi Valley Freight Coalition. MAFC is a regional organization that cooperates in the planning, operation, preservation, and improvement of transportation infrastructure in the Midwest. Its coalition members include ten states (Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Missouri, Ohio, and Wisconsin) that share key interstate corridors, inland waterways, and the Great Lakes. These ten states signed a Memorandum of Understanding in October 2006 demonstrating their willingness to meet freight demand through regional cooperative efforts. The MAFC is built upon the work of the Upper Midwest Freight Corridor Study (UMFCS).

2.4 Regional and Local Agencies

Local agencies include MPOs and other regional agencies, counties, cities, and special districts such as ports.

2.4.1 Metropolitan Planning Organizations

MPOs provide a regional perspective on freight movement, not only identifying congestion and reliability issues, but also explicitly recognizing freight movement as contributing to the economic health of a region. MPO studies of freight movements have brought together a wide variety of stakeholders including city and county governments, port authorities, the business community (including shippers and freight carriers), environmental groups, and the public at large.

A recent presentation on Best Practices for MPO Freight Planning in 2009 noted that there is no single best practice for freight planning, and that freight planning issues should match the issues of the MPO (Cambridge Systematics, n.d.). Freight movement issues in the region can be seen in a number of ways, including as an

- Economic development issue,
- Congestion issue,
- Safety issue, and
- Quality of life issue.

Metropolitan Transportation Commission

MTC developed a regional goods movement study for the San Francisco Bay Area in 2004 (Metropolitan Transportation Commission, 2004). Phase 1 of the study focused on understanding the movement of goods and the economic effects of this industry on the San Francisco Bay Area. Phase 2 assessed both the economic and employment effects of the industry on the Bay Area and its sub-regions. It provided a "big picture" analysis of the industry for policymakers and focused on the interaction among the trends in the goods-movement industry, local policy decisions that affect the goods-movement industry, and the industry's effects on the regional economy.

The intent of the study was to develop strategies for how MTC should allocate investment resources to goods movement in the regional transportation plan. As part of the study, a working paper was produced on developing land use strategy to support regional goods movement in the Bay Area (Hausrath Economics Group and Cambridge Systematics, 2004).

Portland Metro

In 2010 Portland Metro adopted a regional freight plan as an element of its regional transportation plan (RTP) update (Metro, 2010). The intent of the plan was to position the region for the economic rebound after the 2008–2010 recession. The task force targeted the following as the main issues for freight movement in the region:

- Congestion and hotspots—chronic road and rail network bottlenecks that impede regional freight/goods movement;
- Reliability—as distinct from congestion, unpredictable travel time due to crashes, construction, special events and weather (often exacerbated by capacity constraints);
- Capacity constraints—caused by physical and operational issues as well as lack of capacity in critical corridors;
- Network barriers—safety concerns and out-of-direction travel resulting from weight limited bridges, low bridge clearances, steep grades, at-grade rail crossings and poorly designed turns or intersections;
- Land use—system capacity and land for industrial uses that is being lost to other activities; and
- Environmental and other impacts—managing adverse impacts including diesel emissions, greenhouse gas emissions, water quality, noise and land use conflicts.

Sacramento Area Council of Governments

SACOG conducted a regional freight study in 2007 that looked at freight movement in the region in relation to transportation and land use policies (Tioga Group, 2007). The study looked at existing and planned land use policies and also conducted a project analysis of the Metropolitan Transportation Plan (MTP) with specific regard to how projects in the MTP would affect freight movement in the region. Projects were graded specifically on how well they would improve goods movement. Within each grade, the total cost of the projects that received that grade was calculated.

2.4.2 Cities and Counties

Cities and counties regulate freight primarily through their authority to designate loading zones, to restrict truck parking, to prohibit trucks from certain roads, and to designate specific truck routes. Physical characteristics of city roads can also limit truck movements such as height limits imposed by bridges and overpasses (Rhodes et al., 2012). For example, New York City regulates truck traffic in several ways including (NY DOT, *Trucks and Commercial Vehicles*)

- Limiting truck parking to certain areas,
- Prohibiting standing by trucks except for loading and unloading,
- Limiting trailer parking,
- Identifying specific truck routes within the city,
- Developing a pilot off-hour truck delivery program that restricts truck deliveries to certain hours with low traffic, and
- Setting weight and size limits on trucks within the city.

Another example is San Francisco, which has instituted a number of regulatory and advisory measures for trucks including the following (San Francisco MTA):

- Requiring special permits for "extralegal" trucks on city streets (i.e., trucks that exceed 8.5 ft. in width, 14.0 ft. in height, or 65.0 ft. in length or are greater than 34,000 lbs. per axle);
- Designating streets with specific restrictions on truck weights;
- Designating advisory truck routes within the city; and
- Providing a special advisory that trucks, like all other motorized traffic in the city, should share the road with bicycles.

The City of London's transportation strategy focuses on a number of strategies to address congestion and reduce CO_2 emissions. One of the strategies for freight is out-of-hours deliveries (OHD). The department for transport has published guidance on how local authorities can facilitate OHD. Benefits of OHD include (Rhodes et al., 2012)

- Improve driver and fleet productivity,
- Improve the environmental footprint of the logistics operation by operating vehicles more efficiently during times when there is less congestion, and
- Reduce the wider impacts (e.g., crashes, noise, and parking) of logistics operations on the local area.

A trial of OHD performed in the borough of Wandsworth at the Sainsbury supermarket chain found that (Rhodes et al., 2012)

- The average delivery vehicle roundtrip journey times were reduced by 60 minutes from the distribution time;
- OHD produced a saving in drivers' time of 2 hours per day, equal to 700 hours or £16,000 per year; and
- OHD removed 700 vehicle journeys from the road annually (2 per day during the congested period), which is equivalent to a 68-ton reduction in CO_2, and a 700-liter per year savings in fuel.

2.5 Findings from Public Agencies Survey

Surveys and interviews of transportation planners at selected state DOTs and MPOs in 12 states found

1. The majority use HCM methods. The second most common is microsimulation, followed by FHWA's freight analysis framework (which uses the area-wide planning method from HCM 2000).

2. There is a strong preference for truck level-of-service (LOS) methodology for ranking goods-movement investments and evaluating general highway capacity investments.
3. Agencies believe that truck LOS should be sensitive to travel time reliability, traffic congestion, and average speed.

2.6 Conclusions from State of Practice Review

Freight planning and regulation is conducted by a number of agencies at different levels with overlapping authorities. Freight planning issues have been given greater and greater policy importance over the past 10 years as public agencies at the national, state, regional, and local levels have increasingly recognized the importance of efficient freight movement for economic health and regional economic competitiveness.

Freight movement entails a number of issues including economic development, safety, congestion, and environment. Truck LOS is concerned with only some of these issues. This may explain in part why there appears to be no specific examples of use of LOS measures that solely address trucks other than planning studies that address how congestion affects truck movement and shipping reliability.

And yet, recognizing the limitations of LOS, there is strong interest from public agency freight planners in having the ability to apply a truck LOS measure in planning and programming goods-movement projects. This is driven by the desire to "mainstream" consideration of highway freight movement in the process used to identify, prioritize, and program transportation improvement projects by speaking the same language as for automobile projects. Automobile LOS is often used in transportation planning and traffic impact studies to identify deficiencies, determine significant impacts, and develop mitigation measures. The recent development of bicycle, transit, and pedestrian LOS measures for urban streets for the 2010 *Highway Capacity Manual* (TRB, 2010), leaves freight movement on highways as the last major mode of travel without a LOS measure.

SECTION 3

Truck Carrier and Shipper Perspectives

This section presents available information on the perspectives of truck carriers and shippers regarding their use of highway facilities to move goods.

Understanding of commercial vehicle operations by planning agencies has often not moved in lockstep with the demands of the industry. A primary reason has been the misconception among private enterprise that participation in planning studies will require the sharing of proprietary information. A related reason has been the difficulty in recruiting freight establishments to participate in market assessment studies—for example, stated choice surveys—which precede planning and investment. A third reason has been the relatively poor quality of survey data often collected from the few commercial vehicle operators that do participate in the market research efforts.

However, recent efforts in this arena are showing better results, in part because of the growing sense among establishments that public–private partnerships can help provide solutions that improve business performance. This section summarizes key highlights from recent studies conducted by the research team across different parts of the country that highlight commercial vehicle decisionmaking. These research studies cover large metropolitan areas, such as New York, as well as the breadth and width of the country.

The rest of this section is organized as follows: first, an overview of the background of commercial vehicle decisionmaking is presented. Second, the methodology and approach in determining shipper carrier decisionmaking is discussed. Finally, the key findings are synthesized specifically focusing on the impact of performance measures on commercial vehicle decisionmaking.

3.1 Background

There have been several research studies on the value of time and preferences of freight shippers and motor vehicle carriers:

- Smalkoski and Levinson used a stated-preference survey to develop a Tobit model to estimate value of time for shippers. The average time value was $48.72/hour, although the results showed considerable variation across respondents. The study recommended an upper bound of $185/hour (2011 dollars) on commercial vehicle time (Smalkoski and Levinson, 2005).
- Small et al. conducted a stated-preference survey of carriers. They estimated that on average, carriers value travel time savings between $265 and $350 per hour and delay costs at $680/hour (2011 dollars) (Small et al., 1999). A contributing factor to these high estimates may be the types of commodities transported by carriers selected for interview. A number of these carriers transport types of commodities (e.g., agriculture, construction materials) for which the shipper may have to bear the costs of late shipments.

- Fowkes et al. conducted a stated-preference survey of shippers, haulers, and third-party logistics operators to estimate the value of time reliability for long-haul shipments; the average shipping distance for those surveyed was 280 km (174 miles). The results indicate valuations of $189/hour for delay time, $151/hour for arrival time spread, and $116/hour of schedule delay (2011 dollars)[1] (Fowkes et al., 2004).
- Shinghal and Fowkes conducted a stated-preference survey of shippers' mode choice and showed that it was highly related to both travel time and reliability (Shinghal and Fowkes, 2002).

From these studies and others, the following conclusions can be drawn:

- The value of time for trucks is considerably higher than that for passenger vehicles. From that perspective, management and investment decisions on highway capacity and operations improvements need to place a higher valuation on effects on truck traffic.
- Travel time reliability is a prime consideration for the trucking industry. It is typically valued much more highly than travel time, especially for high-value cargoes.

The main focus of this study is to understand the key LOS variables that impact truck movement. However, isolating the impact of LOS variables on commercial vehicle movement is difficult due to the nature of the decisionmaking involved:

- First, commercial vehicle decisions such as routing and time-of-day are governed not just by LOS variables—which are of most interest to this study—but also are influenced by variables such as equipment availability, local governance laws, oversize and overweight permits, and driver travel and rest patterns. Further, the relative importance of these variables differs by establishment, making it very difficult to develop a generalized impact on behavior.
- Second, unlike automobile movements in which all decisions are made by the driver, commercial vehicle movements are controlled by multiple decisionmakers including shippers, receivers, and carriers. Therefore, it is important to capture the perspective of all three stakeholder groups when inferring about the decisionmaking process.
- Third, commercial vehicle movements are governed by economic decisions at an establishment level, and establishments are often secretive about the heuristic rules they employ since they are proprietary and central to their business. While detailed rule-making procedures are unlikely to be fully disclosed by establishments, our research has found that they are willing to share the decisionmaking process at an aggregate level.

This section of the report presents summary findings describing the impact of performance measures on commercial vehicle decisionmaking using findings from shippers, receivers, and carriers. While these findings are not applicable to every truck movement, they provide a good framework for an in-depth assessment of decisionmaking. A variety of market assessment options including focus groups, executive interviews, and survey efforts (and literature reviews) were employed to engage in discussions with commercial vehicle operators in these studies.

3.2 Approach and Methodology

As discussed earlier, findings from three different types of methodology are reported herein: focus groups, executive interviews, and survey efforts. Each of these techniques has been used to identify different aspects of the decisionmaking process as well as differences in use, audience, and findings. Participants are selected based on their relevance to the study, and databases such as InfoUSA establishment data serve as the sampling frames for each of the three methods.

[1] Conversion to 2011 dollars based on an exchange rate of 1£ = $1.60 and an inflation rate of 1.84 between 2000 and 2011.

Trade organizations were a good source to identify and connect with the correct person within a company for participation in these efforts. It was felt that this kind of approach would lend credibility to the survey as well as prepare respondents for receiving the phone call, making them less likely to hang up. Reaching the right person in a company was a bigger issue with large firms than with small firms with a few employees. A "pre-warning letter" was also used to prepare respondents for the study. Letters were seen as a means to potentially help with the challenges of getting through front office gate keepers such as receptionists and administrative assistants. Recruiting new participants through contacts at participating firms—that is, snowball sampling—was suggested as a method to increase participation, although with the caveat that using such a method would have selection bias implications.

The three methods used are described below:

- **Focus groups:** Focus group discussions provide a social platform to engage multiple stakeholders in one discussion. However, they are limited to engaging participants within or close to the study area. Typical recruitment methodology is to send out e-mail invites or recruit via telephone. Typical sessions tend to last between 90 and 120 minutes and are conducted with the help of a moderator. This method has helped capture invaluable qualitative information regarding business operations from shippers, carriers, and receivers provided that the information steers clear of proprietary information.
- **Personal interviews:** One-on-one telephone interviews supplement findings from the focus groups and allow the study team to speak with decisionmakers that operate out of far-off headquarters. They are a powerful means to engage individuals from a specific enterprise to respond to a variety of policy scenarios. The personal interview format works very well to minimize privacy or proprietary information concerns that establishments often have in participating in focus groups.
- **Surveys:** Ultimately, most policy decisions must be supported by a quantitative framework that assesses the net impact of the decision. Surveys are either administered over the phone, via mail or, more recently over the web. Surveys allow study teams to capture information from a large number of establishments and are relatively lower cost than either personal interviews or focus groups. But, because there is limited interaction between surveyor and participant in a survey format, it is important to understand the most relevant decisionmaking variables, the appropriate terminology, and the behavioral aspects of establishments prior to engaging them in a survey. Hence, the qualitative efforts are utilized first to help streamline the survey approach. When creating surveys, it was also critical to provide sufficient descriptions of alternatives so that survey participants could picture viable "real world" situations—for example, costs included a detailed description of all costs involved such as tolls and parking. In real life, large shippers often receive discounts over displayed rates, which must be captured for modeling purposes. Considering a "delivery window" (e.g., 1 to 3 days, 2 to 4 hours) was an acceptable way to incorporate travel time and on-time delivery factors and reflects how decisions are made by firms.

An example project where these three methods were applied was in New York. For this project, which focused on evaluating alternative means of crossing the Hudson River, stakeholders were approached in 2010 using a comprehensive three-phase market research study. First, focus groups and then interviews were conducted with companies that move significant amounts of freight within the New York–New Jersey area (Komanduri, Musti, and Proussaloglou, 2012). Then, a customized stated-preference survey was administered to a broader group of participants to quantify their route, mode, and time-of-day decisionmaking. Appendix C presents interview guides used for this study.

- Focus groups were conducted in New York City; therefore, participants were recruited from a list of companies located within and likely to have freight shipments in the New York (Manhattan), Bronx, Kings (Brooklyn), Queens and Nassau counties. The qualification for

inclusion included transportation of freight shipments across the Hudson River (the main focus of the study). A mix of industries, geographies, and short- and long-haul shippers participated in the focus groups.
- For interviews, employees from five major logistics companies and three large retailers were recruited. All recruited individuals were knowledgeable shipping professionals who held key positions within the logistics arms of their organizations such as transportation managers, chief operating officers, and vice-presidents of supply chain and were based primarily in areas other than the New York–New Jersey region. The three large retailers interviewed include one of the largest drugstore chains, a leading discount warehouse club, and a major household goods retailer. These establishments reported shipping at least 50 million pounds of freight annually. The five freight logistics companies were all large national transportation firms that had a huge operational presence in the region.
- A total of 854 establishments were recruited using telephone interviews to participate in a stated-preference survey. Criteria for selection included firms that moved cross-Hudson shipments, that moved packages of at least 200 pounds, and that use both truck and other modes as the focus of the study was to move trucks off existing crossings. In all cases, most respondents reported limited vehicle ownership and a reliance on trucking firms, logistics providers, and other support to meet their transportation needs. The actual mode and details of shipping was often left to these companies, as long as they fit the cost, timing, and other parameters required by the shippers and/or customers.

Other studies have used similar types of forums and recruited participants in a similar manner. Differences include targeting long-distance shippers, focusing on particular industries, and/or identifying and approaching a wider industry base. However, focus group sizes still remain between 5 and 10 participants to improve the quality of discussion while the number of interviews conducted tends to remain small owing to difficulty in recruiting and retaining high-profile participants for an hour or so. Surveys were designed using either web-based or telephone-based approaches to target larger audiences.

3.3 Shipper Carrier Surveys

As part of this study, a private-sector outreach task was conducted in order to identify the dependence on performance measures by the trucking industry (shipper/carrier/logistical consultants) when making shipping and routing decisions, as well as the industry perceptions of the quality of service provided by streets and highways for freight transportation.

To accomplish this task, a survey was developed by the research team and distributed through a national organization for members of the trucking industry in order to receive a variety of perspectives on these issues. This section discusses the methodology and details the results of this private-sector survey. This survey was also intended for later use in conjunction with a similar public-sector survey to inform the remainder of this study in the development of recommendations for updating the HCM.

3.3.1 Survey Methodology

Through previous survey research, the research team found that the attributes regarded as most important to freight decisionmaking were cost, reliability (on-time delivery), travel time, frequency/flexibility, delivery window, and damage prevention/security/equipment availability. For the purposes of this study, these attributes were grouped into three categories: cost, travel time, and reliability (a category including all of the factors described above, minus cost and travel time). This survey attempted to obtain detailed information about what aspects of these three attributes were most important to shippers and carriers and what characteristics influence the three attributes. In particular, the survey probed respondents on how these characteristics relate to factors such as design and geometry, which are associated with road planning and other functions that utilize the HCM.

Survey Instrument

The purpose of developing this survey was to collect industry perspectives about the critical performance measures that affect the trucking industry. These performance measures were based on and serve to expand the research previously conducted by the research team on trucking industry decisionmaking.

It was determined that the most cost-effective method for reaching a wide audience was to utilize the NCHRP web-survey instrument (documented in Appendix C). Survey respondents were also given a chance to provide additional comments or clarifications after taking the survey.

A total of 21 questions were included in the survey. All questions were marked as optional in order to reduce survey fatigue, to allow survey respondents to focus on questions that directly applied to their business, and to reduce the amount of noise through allowing respondents to skip questions. The questions were divided into seven sections, as follows:

- **Section 1: Context** (six questions). This section asked respondents to provide information about their position in their company; mode choice decisions made by their company (including identifying factors influencing mode choice, e.g., distance, cost); average shipment distance (e.g., long- or short-haul); and the percentage of "just in time" shipments. These questions were developed with the intention of understanding the context in which the decisions regarding shipping and routing that are addressed in the remainder of the survey sections were developed.
- **Section 2: Truck-Based Shipping Decisions** (four questions). This section asked respondents to provide information about how their company makes shipping decisions, who is responsible for making the routing decisions, and factors that affect routing decisions. This section also recorded information regarding respondents' rating on the need for modifying guidelines to road design and geometry for different road types (e.g., freeways, interchanges).
- **Section 3: Overall Values—Cost, Travel Time, and Reliability** (two questions). This section asked respondents to evaluate cost, travel time, and reliability and to rank changes in one attribute to improvements in the other two attributes.
- **Section 4: Cost** (two questions). This section asked respondents to choose factors that affect transportation cost.
- **Section 5: Travel Time** (two questions). This section asked respondents to choose factors used to determine the travel time of a route and to question them on their willingness to pay tolls in order to obtain travel time savings.
- **Section 6: Reliability** (three questions). This section asked respondents to choose characteristics associated with a "reliable" or "unreliable" route. Respondents were also asked their willingness to pay tolls in order to obtain an increase in on-time performance.
- **Section 7: Follow-up** (four questions). Respondents were allowed to record any additional thoughts regarding items of the survey they felt required explanation. They also provided contact information if they were willing to participate in follow-up data collection efforts.

The full survey text is included in Appendix C, unpublished herein but available at www.TRB.org by searching for NCFRP Project 41.

Approach

There are some difficulties that often occur when attempting to recruit respondents for planning studies and surveys. These difficulties include the common misconceptions within the industry that participation in these studies requires the sharing of proprietary information, a difficulty

Exhibit 2. Summary of survey placement.

Organization	Participated? (Yes/No)	Reason Given
The Truckers Report Online Forum - *www.thetruckersreport.com*	Yes	
American Trucking Association (ATA)/American Transportation Research Institute (ATRI) – *www.trucking.org*	No	Declined due to proprietary research requirements
America's Independent Truckers' Association (AITA) - *www.aitaonline.com*	No	Did not respond or declined (no reason given)
Truckingboards Truck Driver Forums – *www.truckingboards.com*	No	Did not respond or declined (no reason given)
Truckload Carriers Association – *www.truckload.org*	No	Did not respond or declined (no reason given)

of recruiting freight establishments to participate in studies, and a lack of interest or time on the part of individuals in private enterprise in participating in these studies. Recent efforts are beginning to show better response to these types of outreach, in particular due to the growing sense among establishments that public–private partnerships can help provide solutions that improve business performance. Regardless, approaching industry for research purposes can be difficult.

For this study, the research team reached out to a variety of shipping and carrier related industry associations for assistance in distributing the survey. The survey was also posted on a national trucking-related forum. However, due to various reasons, including unfamiliarity with the NCFRP research program and proprietary research involvement requirements, most organizations declined to participate in this effort. Exhibit 2 summarizes the results of efforts to reach out to various national and online trucking organizations.

One organization, the Truckers Report Forum, was supportive of the survey and gave permission for the research team to create a forum thread, which was verified and recommended by a site administrator. This verification and recommendation was crucial in presenting the survey as a legitimate (i.e., not "spam") research effort. The website reported over 800 "views" for the posting during the time the survey was active. This forum was found to be particularly effective in reaching truck drivers and trucking fleet owners for the survey. In addition to the survey responses, 18 comments were posted in the Truckers Report Forum thread. Six of these comments are categorized as "feedback" and considered within the scope of the study. The remainder are either administrative or not within the scope of the study. The responses received are included in Appendix C.

3.3.2 Survey Analysis

This section provides an overview of the online survey results. Responses were scrubbed and a total of 39 responses were analyzed. The summary statistics of survey responses for each question are included in Appendix C.

Section 1: Context

A majority of respondents identified themselves as drivers (80%), with the remainder identifying as dispatchers or logistics/shipping executives. Of the respondents, 90% reported that they worked for a carrier, with the remainder reporting working for an owner/operator or private fleet.

In terms of mode utilization, 82% of respondents reported that they exclusively used the truck mode; 8% of respondents also used intermodal or rail. The majority of respondents (72%) reported using at least some long-haul shipments (>8 hours travel time); 30% of respondents had some shipments that were considered local (<2 hours travel time), while 64% reported some shipments as short-haul (2–8 hours travel time). Of the respondents, 28% indicated that greater than 50% of their shipments were time critical, or "just in time," shipments.

When asked to rank issues of importance to their shipping mode choice, almost all choices were ranked as "very important" or "somewhat important" by a majority of respondents. The top choices that were ranked highest as "very important" were on-time performance, delivery time frame, cost of shipment, and damage to goods/security. Similarly, the majority of factors presented regarding route selection were ranked as "somewhat important" or "very important" by most respondents. The top factors ranked as "very important" to route decisionmaking were route congestion, travel time, roadway conditions, and delivery time frame.

Section 2: Truck-Based Shipping Decisions

Several questions were included in the survey to determine who at a particular company controls the routing decisions, with the intention of understanding the perspective of the decision-maker who chooses to use a particular route over another. In every case, respondents indicated that the driver was given some control over route selection. For almost half of respondents, the driver is the primary selector of the route, while a quarter indicated that the route is selected by a dispatcher, but the driver has the ability to modify the route if necessary.

Respondents were asked which road types needed modifications to design/geometry and also were asked to rank each independently on a 1 to 5 scale from "no need" to a "pressing need." The road conditions indicated as a "pressing need" include urban streets, intersections, urban freeways, and interchanges. Fewer than 10% of respondents indicated that roadway design/geometry modifications were not needed on any particular road type.

Respondents indicated that a range of factors influenced route selection decisions. Truck parking and traffic congestion were rated as "always being considered" by a third of respondents, while roadway grade and pavement quality were always considered by a quarter of respondents. Availability of truck lanes was the only choice "never" considered at a higher rate than "always" considered.

Section 3: Overall Values—Cost, Travel Time, and Reliability

When asked to decide between reduced cost, reduced travel time, or increased reliability, responses were close to evenly split: 26% preferred a 10% reduction in travel time, 23% preferred a 10% reduction in cost, and 18% preferred a 10% increase in reliability. When asked to make a tradeoff between two of these factors (e.g., increased reliability with a corresponding increase in cost or decreased travel time with a corresponding decrease in reliability), responses were split across the various permutations. The most common response (23%) indicated that respondents were unwilling or unable to make a tradeoff and would prefer that the three variables remain static.

Section 4: Cost

Many factors were viewed as adding to the "cost" of a truck route. The factors identified as affecting transportation costs were distance, travel time, time of day, delivery window, route congestion, and roadway conditions. Factors attributed to the "cost" of travel on a particular roadway were tolls, vehicle wear and tear, traffic congestion, and cost of delay. Other factors not included in the survey but identified by respondents include fuel prices and reload availability.

Section 5: Travel Time

Less than half of respondents indicated that their company took action to minimize or manage travel time on a route. Factors that are adjusted to minimize or manage the travel time of a shipment include using the shortest distance route or adjusting the time of day/delivery window. Factors not included in the survey but added by respondents included avoiding city rush hours and taking the "fastest route." When asked how much they might be willing to pay to decrease travel time by 10% (as a percentage of cost), 43% of respondents indicated "nothing," while only 10% of respondents indicated that they would be willing to pay any amount.

Section 6: Reliability

Out of the three focus characteristics of cost, travel time, and reliability, the latter appears to be highly associated with road design and characteristics. The survey asked what characteristics would be attributable to a reliable route. The most common response was high quality road (e.g., level terrain, wide lanes and shoulders, good pavement), followed by few intersections or traffic stops, no known construction, and "route my company uses often." Conversely, characteristics of an unreliable route rated by a high number of respondents include poor road quality, high traffic volume, traffic congestion (51%), multiple intersections or traffic stops, and construction. Lack of truck parking was also selected by more than one-third of respondents as a characteristic of an unreliable route, and the truck parking issue was also brought up in several respondents' free response comments. Few respondents reported a willingness to pay to increase their reliability.

Section 7: Follow-up

Five respondents indicated that they would be willing to participate in a follow-up interview and provided phone and/or email contact information. Four of these respondents, and five additional respondents, included additional comments, a sample of which follows:

- "As a 10-year driver through 48 states, I will say that our highway system is terrible. I-5 in CA is bad, I-70 through IN and OH is bad. Certain states leasing toll roads to companies is really bad. There is a huge lack of truck parking in many states. I route myself away from many states due to road conditions, so I don't buy fuel or spend money in these states as a result."
- "I went to school for Civil Engineering/Land Survey—where do I begin other than the fact most designers have NO CLUE what it's like to pilot an OTR truck down the road. I'd make every designer in the DOTs get a Class A CDL and have them all get some road experience."
- "We regularly route around toll roads. They are much too expensive and are usually poorly maintained. We pay more than enough in fuel taxes to eliminate toll roads completely."
- "On the unreliable delivery time, we haven't had that problem. We allow flex time for unanticipated delays. We have good reliability and think we know within the company how best to improve it."

3.3.3 Discussion

Although the findings of this survey represent a limited sample of industry perspectives and do not represent a detailed cross section of road users, several themes do emerge that provide valuable information on the preferences and perceptions of the freight trucking industry. It is clear that many aspects of road design and geometry, as well as the issues of congestion and road conditions, play a role in the broader decisions made by the freight industry. Overall, this survey served as a confirmation that the issues of cost, travel time, and reliability are important and often interwoven concerns that influence business decisionmaking.

The interplay between cost, travel time, and reliability is complex, and many of the underlying measures contribute to more than one of these issues. In particular, the distance traveled, road congestion and condition, and time of day/delivery window factors play a part in multiple issues. Findings show that respondents were able to make the connection between factors of road design and geometry and these issues of interest—for example, vehicle wear and tear and the cost of delay were both seen as contributing to the "cost" of choosing a road by 40% to 50% of respondents. Respondents were also able to identify factors that made a road "reliable" or "unreliable," particularly road quality, traffic volume or congestion, and intersections/traffic stops. These factors in particular are influenced by the planning process and road design and, thus, represent candidates for truck-specific factors to be incorporated into the HCM.

When asked about the types of roads needing design/geometry guideline modifications to better serve trucks, findings show that overall the respondents believe that there is a high need for modifications on all road types. Two out of three respondents reported a need for modifications to urban and non-urban freeways and other highway types, interchanges, urban streets, and intersections. This confirms the intention of this project—that there is a need to better incorporate truck considerations into the planning process. When asked about specific types of roadway/geometric factors influencing their route selection, truck parking, traffic congestion, and pavement quality received the highest number of responses, indicating that they were highly influential in route selection.

Respondents were less concerned with the availability of truck lanes or the design of intersections. These findings indicate that the respondents in the study appear to be aware of road and route geometry and characteristics and incorporate these into their planning and operations. Hence, it makes sense to have improved standards by incorporating variables that are currently missing in the HCM such as reliability, travel time, and transportation cost and to tie them to road design or geometry parameters that are used by road planners.

Finally, although respondents were able to identify areas that they felt needed improvement, they were less willing to make a tradeoff between different factors of importance (i.e., cost and travel time). In the business world, many companies have likely already made these tradeoffs to find the business models that work best for their company. Hence, it is understandable that companies might be reluctant to pay more or reduce some aspects that are important to them even if it does provide a savings in another area.

3.4 Findings from Shipper Carrier Survey

This section synthesizes the key findings from the different studies. They are organized under broad topical areas. Special emphasis is placed on the LOS variables that are most relevant to this study.

3.4.1 Decisionmakers

Control over decisionmaking varies depending on the size of the establishment and the amount of freight the establishment moves annually, as well as the role of the establishment in the logistics supply chain:

- In general, receivers and shippers that do not own their own fleet tend to control time-of-day for pick-up and delivery while leaving the routing decisions up to carriers.
- However, small shippers and receivers that move a limited amount of freight each year have limited control over decisionmaking and are dependent on rules employed by transportation service providers.
- In fact, depending on the nature of goods being delivered and the establishments being served, delivery windows varied from “a fixed time” to “over six hours.”
- Receivers and shippers that manage their private fleet, on the other hand, control all aspects of decisionmaking and are involved in developing customized logistics chains.

Many respondents commented that they had limited time during work hours to take a phone survey. Most commented they would be willing to give 10 minutes, although a few said they would only give 5 minutes. Hearing the name of an official organization early in the call made respondents pay more attention and prevented hang-ups. Some wished to hear answers to “what’s in it for me” type questions during the survey.

3.4.2 Decisionmaking Variables

Establishments evaluate several attributes when making freight decisions. In interviews conducted across our studies, respondents identified transportation costs, travel time and reliability as the top factors in making freight decisions. Other related issues such as local governance laws for delivery times and routing were also critical to decisionmaking. In some urban areas, toll and parking costs are also important inputs to decisionmaking.

Focusing on shipments across the Hudson, respondents developed a list of attributes that were important in their consideration of transportation modes and services. Participants were asked to rank a list of transportation factors that are considered in mode choice based on their importance in the consideration process using a 10-point scale, with 10 being the most important and 1 being the least important. The three most important attributes were cost, reliability and delivery time, followed by security features and avoidance of shipment damage. In addition, special needs of certain shipments were found to impact consideration of shipment mode. Results are summarized in Exhibit 3.

Other decision factors include the ability to track the shipment from origin to destination. Tracking was important to most participants who move freight, although some placed more emphasis on this as a decision factor than others. Customer service was not immediately recognized as a key decision factor, although discussions revealed that it was important when selecting a transportation service provider. Firms with poor customer service records, particularly related to on-time reliability and/or damages, were often not selected to move shipments.

Exhibit 3. Attributes central to freight decisionmaking in New York and New Jersey.

Factor	Ranking*	Notes
Cost	10	Ranked consistently across the board
Reliability (*On-Time Delivery*)	10	Typically considered slightly less important than cost
Travel Time	9	Related to On-Time Delivery. Customers are normally informed of a specific timeframe for delivery, developed by using total travel time and other factors.
Frequency – Flexibility	9	Frequency and flexibility of shipment arrangements are a factor in mode choice
Damage Prevention/Security Transportation Equipment Supply	9	Prevention of damage to goods and ensuring safe arrival were very important. Having the right equipment and personnel is seen as a necessary step.
Payment Terms	6	Not regarded as important
Special Handling Equipment Customer Service Technology Origin and Destination Restraints	Low (<5)	These were all rated as relatively less important. However, when problems develop in these areas, special equipment needs, customer service and technology capabilities, and work rule/time slot restrictions can become extremely important.
Environmental Considerations	Very Low (<3)	Respondents whose companies were responsible for the disposal of environmentally sensitive materials rated this consideration as important. Generally, environmental issues, carbon footprints, etc., are not included in the transportation managers' perspective.

*10 is "most important" and 1 is "least important."

Highway versus Non-Highway Modes of Transportation

Several factors influence modal decisions:

- The shipping needs of the business translated as the nature of the goods being moved has a critical impact on the modal selection. For instance, bulk goods such as coal are almost always shipped on rail irrespective of freeway performance.
- Trip length also influences modal selection. For instance, shippers in New York reported that they would never choose rail for trips shorter than 400 miles.
- The service provided by competing modes is a critical factor in modal determination. For instance, rail has a relatively higher mode share to a central location such as Chicago whereas New York City, which has poor freight rail service, has about 2% of rail mode share.
- Interviewed establishments reported relying on rail for at least some long-haul shipments, primarily motivated by lower costs. In general, establishments identify rail as a low-cost, slow mode of transportation. Retailers reported making tradeoffs routinely while making modal decisions.
- Some firms reported a strategy of avoiding congested routes at all costs. Approaches using alternate roadways or shipping goods by rail or air were preferred.

Participants from larger establishments in focus groups across the country reported dealing directly with trucking firms for their shipment needs. A majority were less inclined to deal with shipment details (e.g., whether shipment went by rail) and were interested only in knowing that shipments arrived as scheduled in undamaged condition. A few respondents reported interest in knowing the specifics about all modes and carriers used. The concern was that an intermediate carrier might be a "Mom and Pop with no insurance" and, therefore, less reliable. The possibility of damaged goods or late delivery with the introduction of rail or other modes was also the cause of some unease.

Supply Chain Logistics

Most large establishments utilize distribution centers, which operate as "hubs" between vendors and retail establishments. Respondents reported that operating these hubs improved transportation efficiency as vendors were able to ship goods destined for many stores via the same carrier. Distribution centers allowed retailers to operate using different shipping strategies:

- The most commonly reported—"just in time" type shipping—allows goods to ship to the store at the last opportune moment. This type of shipping minimizes warehousing and stocking costs and increases their ability to conform to their customer's needs; however, it does place a higher burden on the transportation system and demands higher reliability.
- The second strategy—"managing shipments based on the predictability of lead time"—is sometimes used in which store-managers are expected to place orders at the appropriate time to supply their inventory needs. This type of shipping may incur inventory stocking fees, but allows for more flexibility in delivery and travel times.

These supply chains are dependent, to a large extent, on the reliability of transportation services. In fact, several participants reported choosing slower options that were more reliable than the fastest service.

Carriers typically break down a long-haul trip into a series of smaller legs depending on the location of their distribution centers. Typically, a trip from New York to California may be broken down into three legs with stops at two intermediate distribution/consolidation centers. At each of these distribution centers, carriers consolidate or break down their loads depending on the final destination and number of trucks available to make the trip. Should enough trucks be not available at any one or more of these intermediate stages, carriers may choose to move goods on rail to maintain efficiency and meet the travel time requirements for the goods being shipped.

Long-Term Contracts

Retailers reported using a bidding process to determine the most efficient way to ship goods across the country. The carriers are made aware of the shipping strategy of the company and are expected to price their bids accordingly. For instance, a "just in time" shipment may need to be delivered in a relatively short timeframe while the general replenishment of an in-stock item running low may have a delivery window of a few days. Depending on the volume of goods shipped, they are often provided large discounts over the "spot rate" provided to smaller shippers. "Spot rate" roughly translates to the highest possible shipping rate between an origin-destination pair. Retailers reported paying close attention to both on-time delivery and damages. While not stated explicitly, it is understood in the commercial movement circles that these factors play a role in identifying the most competitive bidder.

Typically, goods were classified into four categories based on volume—parcel, less than truckload, full truckload, and intermodal load. Some retailers reported selecting different carriers for different volumes of goods being shipped. Logistics firms reported tailoring their shipping choices to meet the requirements of their client. In several cases, the clients often made modal decisions for goods movement. This is more apparent among larger clients who ship enough volume to justify making modal decisions for the logistics firms.

Establishments reported that in many cases, customers would specify a shipping preference. This was more common when customers had an existing shipping contract or had negotiated a lower cost rate with a specific carrier than the manufacturer could quote. Transportation managers usually welcome this because they are unlikely to be held responsible for any transportation related incidents. In instances where the manufacturer has a better rate for shipping than the customer, their routes are selected. In these cases, the transportation manager informs the customer, who, in turn, makes the final carrier selection. A similar consideration process occurs with regards to suppliers. Depending on the materials being shipped, the manufacturer may stipulate shipping requirements, but, in many cases, the supplier makes the shipping decision.

Routing Decisions

Several carriers reported making detailed route maps for their drivers and tracking the movement of trucks along the way. Drivers were instructed to contact their dispatch officer if they anticipated having to deviate more than 5 miles from their assigned route. Routing decisions for most large firms were made using custom route optimization software products. Routing decisions vary depending on the length of the trip. Local deliveries are often carried out on congested, local arterials whereas long-haul deliveries are almost always made using freeways and major roadways.

A study in Los Angeles found the following with regard to routing decisions:

- More than three-quarters (77%) of companies used a routing system that was either manual or a combination of a manual system and an automated system. Twenty-one percent of the firms indicated that routing was handled by the drivers, and this was more prevalent among firms with 25 or more trucks, whereas 29% said that drivers handled routing, compared with 18% for firms with fewer than 25 trucks.
- Of the companies surveyed, 38% reported that they relied, at least in part, on Automatic Vehicle Location (AVL) systems or Global Positioning Systems (GPS) or technologies for fleet management. More than one-half of the firms (54%) with a fleet size greater than 25 used such a system, compared with just under one-third (32%) of firms with smaller fleet sizes that employed AVL/GPS as a fleet management tool.
- Information sources with direct impacts on time had the highest overall value to respondents. On a 5-point scale where 1 is least valuable and 5 is most valuable, knowledge about queue lengths at the Port of Los Angeles and Long Beach scored the highest at 4.03. Real-time route information between origin and destinations also had a high value to respondents, with a mean rating

of 3.83. Travel times along freeway segments and information about the location of bottlenecks with travel time through the obstructed area received similar ratings at 3.74 and 3.70, respectively.

- Of the drivers surveyed, 90% used information to change routes as appropriate, either in-route (47%) or before leaving (43%). However, only 11% used it to change pick-up/delivery times or to accept or decline assignments. This suggests that there is limited flexibility in drivers' ability to determine when they are on the road.
- Knowing the fastest routes, the location and delay time associated with bottlenecks, and times to travel different freeway segments were all assessed as top value information.
- The key improvements desired by drivers included better freeway traffic information and information that was easier to use, more accurate, and delivered faster. Each of these improvements was rated as useful or very useful by at least 90% of drivers, suggesting that there is a strong desire to see better delivery of accurate and actionable information.

Key Routes and Governance Laws

Evidence gathered from the research suggests that truckers prefer using Interstates and major roads for the majority of trips. These roadways are preferred for their limited stops, sufficient clearance and for providing reasonably fast service between origins and destinations. However, research from a project in Los Angeles indicated that the use of surface streets for goods movement also depended on the length of the overall trip. For instance, for trips where the average trip distance was less than 50 miles, 80% of the trips involved use of a surface street, compared with only 55% of trips longer than 50 miles.

On a related note, truckers are precluded from using certain roadways based on local governance laws. For instance, in New York City, several parkways preclude commercial vehicles from operating on them. Such laws have an impact on routing, and operators are forced to choose less optimal routes for travel between an origin-destination pair.

Oversize/Overweight Truck Movements

In addition to the typical LOS attributes considered by most truckers, oversize/overweight (OSOW) trucks must focus on additional factors when selecting which roads to travel. Often, OSOW vehicles must submit specific routings when applying for a permit. Both the trucking company and the permit-issuing agency have concerns specific to or more enhanced for OSOW trucks. In many cases, the lowest cost or more direct route may not be available due to infrastructure or classification restrictions. Some of the most common factors for OSOW trucks are summarized in Exhibit 4.

3.5 A Model to Quantify Quality-of-Service Perceptions

Numerous studies of freight transport economics and the shippers' decisionmaking process show that the choice to ship via truck and the choice to ship via a specific motor vehicle carrier hinge on cost, time, and reliability. Virtually all other factors, such as pavement quality, and safety, can be captured via a combination of cost, time, and reliability. For instance, pavement quality and collisions affect a carrier's operating costs (through higher insurance rates, lower reliability, and more frequent tire replacements), which translate into higher fees charged to shippers and less assurance of making the delivery on time. It is critical to understand the relative importance placed on each of these measures so that they can be appropriately weighed and fed into a truck LOS calculation. Therefore, researchers have worked towards quantifying the relationship between travel time, distance, reliability, and shipment costs in freight decisionmaking.

The research team developed a series of choice models that aim to capture this very relationship in a New York and New Jersey study. Key findings include that shippers, receivers, and carriers contribute equally to freight decisionmaking; cost, travel time, and on-time reliability affect decisions; and respondents value their participation in surveys at $100 per hour and prefer

Exhibit 4. Impact of local laws on oversize-overweight truck routing decisions.

Factor	Description	Truckers' Responses
Roadway Classification	Interstates, U.S. highways, and state highways are generally built to withstand heavier loadings and higher traffic volumes than other roads.	Truck routes must be designed to avoid any roads not accessible to trucks and often utilize truck routes and/or highways when possible.
Mileage	Minimize impacts from OSOW vehicles on public safety and infrastructure by encouraging or requiring agencies to use the shortest routes that are possible using roads built to handle OSOW traffic (e.g., Interstates).	When selecting a route, may utilize strategies such as "ramping," which allow trucks to exit and then re-enter a facility in order to avoid a particular bridge or obstruction, instead of following a longer route avoiding the facility with the obstruction all together.
Local Permits	States can provide permits for state and federal roads. Municipalities can require additional permits for locally owned or maintained roads.	Need to balance permitting time, cost, and requirements of a local route versus a longer bypass route.
Corridor Routes	Some states have designated corridors or "preferred routes" for OSOW traffic.	Preferred routes can reduce effort required to plan a route and receive a permit, but may not be the shortest possible route.
Other Restrictions	Routes that would normally be acceptable for OSOW traffic can be restricted or banned for reasons including time-of-day, and political, seasonal, and construction-related reasons.	Certain routes or urban areas have time restrictions. Depending on the move schedule, carriers will use this as a factor in selecting a route. If there is a delay on a route that will force them to stop travel, they will avoid the route.
Bridge Limitations	Heavier loads are requested or required to not cross restricted bridges and infrastructure. If a crossing is required, trucks may be required to wait for a particular time window, obtain pilot cars, or follow other restrictions, increasing time and cost.	If possible, carriers will often avoid bridges and facilities that have additional restrictions.
Intersection Limitations	Some intersections, including roundabouts and traffic circles, are not designed for OSOW trucks.	Routes must avoid these intersections. Generally more applicable to larger loads.
Inspection Stations	Fixed or mobile sites where state or federal personnel conduct safety, permitting, weight, and other inspections of vehicles.	Trucks may avoid roads with inspection stations in order to save travel time and/or avoid inspection.

to be recruited over the phone for short surveys. These findings are in line with earlier studies on freight decisionmaking such as those performed by Danielis et al. (2005):

- Respondents were shown two truck route variations and were asked to make tradeoffs based on on-time reliability, travel times, and transportation costs. Through a binomial logit model, reliability emerged as an important factor, and high reliability routes (>90%) were preferred over medium reliability (85% to 90%) and low (<85%) reliability routes.
- As expected, higher transportation costs and travel times negatively impact route choice (Danielis et al., 2005). Interestingly, both of these variables were found to impact behavior differently for different commodities. In fact, establishments reported varying sensitivities to cost based on the commodity being shipped, the distance of travel, and the time taken to travel between origin and destination.
- There was a non-linear sensitivity to cost—that is, for moves with higher transportation costs, respondents were less sensitive to a dollar increase (decrease) in cost when compared with moves with lower transportation costs. Similarly, long-haul movers were less sensitive to unit increases in travel time when compared with short-haul movers. These results suggest that long, expensive shippers are less interested in unit savings in cost and time. This is a critical observation which suggests that shippers making long trips must be presented with larger travel time (or cost) savings to influence behavior to the same extent as short trips.

The calculated values of time varied from as low as $5.00/hr for long-haul movers shipping bulk commodities such as coal to as high as $170/hr for short-haul moves transporting high-end consumer electronic goods.

Equation 1 presents the binary route preference utility model fitted to the New York/New Jersey panel survey. This model captures the sensitivity of decisionmaking for alternative truck routes. The estimated parameter values are presented in Exhibit 5. Exhibit 6 presents the values of time suggested by the choice model.

$$U = LR + MR + A_G * SC + CS * Max(0, SC - 900) + CT * ETT + TS1_G * Max(0, ETT - 12) + TS2 * Max(0, ETT - 25) \quad \text{Equation 1}$$

where

U = expected utility of shipping route;
LR = dual value variable;
= –0.758 if shipment is expected to be on-time with less than 85% probability,
= 0 otherwise;

Exhibit 5. Route preference choice model.

	Coefficient Description	Value	*T*-Stat
On-Time Reliability	Low Reliability (<85% on-time)	–0.758	–4.4
	Medium Reliability (85-90% on-time)	–0.275	–1.4
Shipment Cost	Cost Agricultural Goods	–0.0108	–4.4
	Cost Metal and Mining Goods	–0.0095	–5
	Cost Construction Goods	–0.0086	–7
	Cost Chemical Goods	–0.0092	–6
	Cost Wood and Paper Goods	–0.0109	–5.6
	Cost Electronics Goods	–0.0099	–5.2
	Cost Transportation and Utility Goods	–0.0060	–4.1
	Cost Wholesale and Retail Goods	–0.0068	–7
	Cost Spline (Applied if Cost > $900)	0.0053	5.7
Travel Time	Time (hr)	–0.320	–5.6
	Time Spline 1 (Applied if TT > 12 hr) Agricultural Goods	0.237	3.6
	Time Spline 1 (Applied if TT > 12 hr) Metal and Mining Goods	0.173	3.1
	Time Spline 1 (Applied if TT > 12 hr) Construction Goods	0.166	3.2
	Time Spline 1 (Applied if TT > 12 hr) Chemical Goods	0.146	2.4
	Time Spline 1 (Applied if TT > 12 hr) Wood and Paper Goods	0.156	2.8
	Time Spline 1 (Applied if TT > 12 hr) Electronics Goods	0.135	1.7
	Time Spline 1 (Applied if TT > 12 hr) Transportation and Utility Goods	0.205	3.8
	Time Spline 1 (Applied if TT > 12 hr) Wholesale and Retail Goods	0.174	3.6
	Time Spline 2 (Applied if Travel Time >= 25 hours)	0.109	2.6
	Pseudo R^2 (0)	0.415	
	Pseudo R^2 (c)	0.324	
	Number of Observations	716	

Notes:

- Student's "t" statistics greater than 2.0 or less than -2.0 generally indicate that the value of the coefficient is significantly different from 0 at the 95% confidence level.
- Pseudo R^2(0), the correlation coefficient, indicates the quality of fit compared with a constant 0 value. A value of 1.0 is exceptionally good, a value of 0.0 is exceptionally poor.
- Pseudo R^2(c) indicates the quality of fit compared with a constant mean value of the data.
- A spline is a variable that takes on a specific constant value only for a specific range of another variable.

Exhibit 6. Values of time suggested by the choice model.

Value of Time (per hr)	*Cost<$900 Time>24 hr	Cost<$900 12<T<24 hr	Cost<$900 Time<=12 hr	Cost>=$900 Time>24 hr	Cost>=$900 12<T<24 hr	Cost>=$900 Time<= 12 hr
Agricultural	—	$7.69	$29.63	—	$15.09	$58.18
Metal and Mining	—	$15.47	$33.68	$9.05	$35.00	$76.19
Construction	$5.23	$17.91	$37.21	$13.64	$46.67	$96.97
Chemical	$7.07	$18.91	$34.78	$16.67	$44.62	$82.05
Wood and Paper	$5.05	$15.05	$29.36	$9.82	$29.29	$57.14
Electronic	$7.68	$18.69	$32.32	$16.52	$40.22	$69.57
Transportation and Utility (TU)	—	$19.17	$53.33	$8.57	$164.29	—
Wholesale and Retail	$5.44	$21.47	$47.06	$24.67	$97.33	—

*Cost is shipment cost.

MR = dual value variable,
= –0.275 if shipment is expected to be on-time with between 85% and 90% probability,
= 0 otherwise;
A_G = shipping cost parameter for good type "g" values as shown in Exhibit 5;
SC = shipment cost (\$) (note: average shipment size in survey was 2,000 lbs);
CS = cost spline constant of 0.0053 added for shipments over \$900 in cost;
CT = –0.320, the expected shipping time parameter;
ETT = the expected shipping time (hr);
$TS1_G$ = Time Spline 1, an additive constant for good type "g" that is applied only if the expected shipping time exceeds 12 hours; values as shown in Exhibit 5; and
$TS2$ = Time Spline 2, an additive constant value of 0.109 that is applied only if expected shipping times are 25 hr or greater.

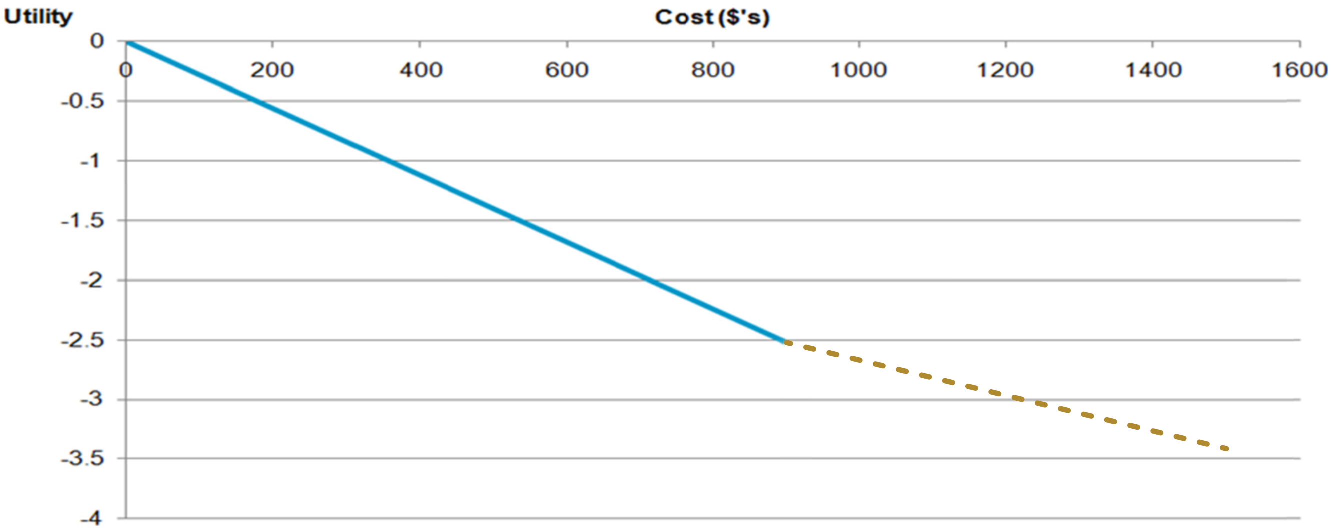
The route choice models clearly indicate that a single value of time often used in demand models to describe freight movement is an extreme simplification. This research suggests that values of time vary by distance, shipment cost, and commodity. Further, results suggest that shippers who move high-value commodity goods over short distances are more likely to embrace policy options such as congestion pricing in return for improved travel times than are others.

The model also reveals that short-haul shippers would choose highway alternatives that could generate a 1-hr savings in travel time for a toll of up to \$30 over current toll rates in the New York region. However, most long- and short-haul shippers are likely to switch to less congested and circuitous routes that take 1 to 2 hr longer if a new \$60 toll were imposed on the most congested and direct routes. While unlikely, a variable toll by commodity could be enforced to impact congestion and freight behavior at a finer level.

It is important to note that the model highlights findings from a highly customized study conducted in New York. The findings from that study should by no means be applied without properly understanding the context of that study. We merely present the model to highlight the point that decisionmaking is affected by multiple factors such as cost, travel time, and reliability. Sensitivity to a host of other qualitative factors such as establishment location, customer preferences, and urgency, while not explicitly captured by the model, are captured by the constant:

- The route preference model helps compute the probability of choosing a particular route. For instance, if a shipper is faced with the task of shipping a commodity from Point A to Point B and has two potential routes available, the route preference model may be used to calculate

Exhibit 7. Example of cost spline effect on utility curve.



the probabilities of each route being selected based on measurable characteristics such as transportation costs, travel times, and reliability of the routes.

- The negative coefficients on travel time in the model suggest that if a particular route has a higher travel time, then that route has a lower utility and is more likely not to be chosen for the shipment.
- A time spline is a variable that indicates the impact of a variable after a specific range on the utility of a choice is slightly different. For example, in Exhibit 7, the solid line indicates the negative directionality of cost, and the dashed line lowers the negative effect and creates a kink in the utility at cost $900.
- The *t*-stat (Student's *t* test) is a test to measure the statistical significance of the estimated coefficients. A *t*-stat value greater than 1.96 for positive coefficients and less than −1.96 for negative coefficients indicates that the value of the coefficient is significantly different from 0 at the 95% confidence level (thus, rejecting the null hypothesis).

3.6 Conclusions on Carrier and Shipper Perceptions

The interviews and survey of shippers and carriers indicate that freight decisionmaking is complex and often varies by establishment. In addition, the criticality of travel time and on-time delivery varies by a factor of 10 depending on the cost of the material being hauled and the distance hauled (travel time). Lower valued goods hauled for longer distances (or times) have the lowest value of time. Therefore, it is very difficult to develop one unique set of criteria that fit all establishments. However, it is possible to develop a general assessment of criteria that fit most establishments using detailed marketing research approaches.

In general, travel time, cost and reliability (on-time performance) are the key determinants of route selection. Local laws, long term contracts between shippers and receivers, the type of goods being shipped, transportation costs and travel times, and logistics supply chains all impact the relative importance of these attributes in decisionmaking of shippers, receivers, and carriers.

In conclusion, the three most critical highway-related factors affecting motor vehicle carrier and shipper perceptions of the quality of service provided by the highway facilities on a given route are: the shipment time (travel time), the probability of on-time arrival (reliability), and the transport cost for the shipment.

SECTION 4

Literature Review

The Transportation Research Information Database (TRID) (TRB) was scanned to identify publications within the past 10 years that are relevant to the key topics of this project. The key topics investigated in this literature review were

- Treatment of effects of other modes on trucks in the HCM 2010, in other guides internationally, and in research;
- Treatment of truck effects on other modes (i.e., automobile, bus, bicycle, pedestrian) in the HCM 2010, in other guides internationally, and in research;
- Truck classification schemes—weight-based, axle-based, and length-based;
- Integration of trucking needs into transportation investment decisionmaking—typical planning studies involving freight movement (case studies);
- Key highway performance criteria critical to shippers and carriers; and
- Sources of data on truck movements (which will be important to future users of the HCM truck analysis method).

The literature review also investigated how the effects of trucks on other modes and the effects of highway performance (and other modes) on trucks are treated in major highway capacity manuals worldwide. In addition to the United States' *Highway Capacity Manual* (TRB, 2010), the team evaluated highway capacity guides from several countries, including

- Canada's *Capacity Guide for Signalized Intersections* (Canadian Institute of Transportation Engineers, 2008);
- The United Kingdom's *Design Manual for Roads and Bridges* (Department of Transport, Highways Agency);
- Australia's *Guide to Traffic Management* (Austroads);
- Germany's *Highway Capacity Manual* (FGSV, 2001);
- India's *Road Congress Guidelines* (Indian Roads Congress, 1994); and
- *The Indonesian Highway Capacity Manual* (Indonesian Directorate General of Highways, 1993).

4.1 Critique of the HCM 2010

This section evaluates the 2010 *Highway Capacity Manual* (HCM) (TRB, 2010) from two perspectives: its ability to predict the specific performance of trucks and its ability to model the effects of trucks on the traffic stream.

Regarding the ability of the HCM to predict the specific performance of trucks:

- The HCM does not provide methods for estimating truck speed and performance as distinguished from that of the passenger vehicle stream.

- The HCM methods, MOEs selected, LOS thresholds, and so forth are based on expert opinion and not validated with freight drivers except for the Urban Streets Method (Chapter 17). The method does not identify measures of effectiveness that reflect the perspectives of motor vehicle shippers and carriers.
- The HCM does not currently predict travel time reliability—a performance measure of critical concern to shippers and carriers.
- There is no specific truck LOS methodology in the 2010 HCM. With the exception of the Urban Streets Methodology, where adjustments are made to the saturation flow rate, trucks are treated using an adjustment factor to the demand (by means of passenger car equivalent [PCE] factors).

Regarding the ability of the HCM to model the effects of trucks on the traffic stream:

- The HCM truck classification scheme is extremely simplistic, not reflecting the spectrum of truck performance capabilities in the U.S. fleet.
- The HCM PCEs are too simplistic since they do not reflect the variation in the truck fleet or the influence of truck proportion or grades on urban street PCEs.
- The HCM PCE look-up tables stop at 25% trucks (as a percentage of total traffic flow) even though there are many facilities in the United States where trucks routinely exceed 25% and can exceed 50% of the average daily traffic flow.
- The HCM treatment of trucks is inconsistent across chapters. Most notably, the uninterrupted flow chapters use a volume-to-PCE conversion method early-on in the procedure. Many interrupted flow chapters use PCEs directly to adjust methodology parameters (e.g., saturation flow rate adjustment for signals).

4.1.1 How the HCM Currently Models Trucks

The 2010 HCM defines three heavy-vehicle types: transit buses, recreational vehicles (RVs), and trucks. These three types are grouped in the HCM under the broader category of heavy vehicles. A heavy vehicle is defined in the HCM as "A vehicle with more than four wheels touching the pavement during normal operation." In the HCM, buses, recreational vehicles, and trucks are considered heavy vehicles with the following special characteristics:

- A bus is defined as "A self-propelled, rubber-tired road vehicle designed to carry a substantial number of passengers (at least 16) and commonly operated on streets and highways." (Equivalent to FHWA Class 4.)
- A RV is defined as "A heavy vehicle, generally operated by a private motorist, for transporting recreational equipment or facilities. Examples include campers, motor homes, and vehicles towing boat trailers." (Generally equivalent to FHWA Class 5.)
- A truck is defined as "A heavy vehicle engaged primarily in the transport of goods and materials or in the delivery of services other than public transportation." (Equivalent to FHWA Classes 5–13.)

Each heavy-vehicle type can be assigned its own PCE rating for the purposes of capacity and operational analyses. However, in most cases, the HCM groups these vehicle types together. Buses and trucks are usually assigned identical PCE values while RVs are generally assigned a slightly lower PCE value. The value of PCEs ranges from an assumed fixed number (e.g., signalized intersections, roundabouts) to a detailed PCE-estimation procedure (e.g., uninterrupted flow chapters).

In general, most HCM chapters convert heavy vehicles to equivalent passenger car units and add them to the passenger car volumes to obtain the total equivalent passenger car volume that is used in the HCM methodologies. The HCM analysis then estimates the capacity, density, speed, delay, and LOS for the equivalent passenger car stream. Truck speeds and delays are not isolated from the values predicted using the equivalent passenger car stream performance. From a performance perspective, none of these covers weight-to-horsepower ratios, which are a key measure of performance.

The impacts of trucks on other modes are modeled differently in the HCM according to the facility type:

- On freeways, multilane highways, and two-lane highways, the grade affects the PCEs for trucks. The number of trucks affects the equivalent passenger car volume, which in turn affects the density and speed of traffic.
- On urban streets, the PCE equivalent of trucks is independent of grade. The number of trucks affects the estimated saturation flow rate, which in turn affects speed and therefore automobile and transit LOS.
- The HCM methodologies for estimating bicycle LOS are sensitive to the percentage of trucks in the traffic stream. For multilane and two-lane highways, the grade or general terrain affects the result by affecting the truck PCEs used to compute the average speed of the passenger car equivalent traffic stream. For urban streets, the percentage of trucks directly affects the bicycle LOS.
- The HCM methodologies for estimating pedestrian LOS are indirectly sensitive to trucks. Higher truck volumes result in lower estimated average automobile speeds, which in turn positively affect pedestrian LOS. (This is no doubt an unintended side effect of excluding the direct effects of trucks in the pedestrian LOS model.)
- The HCM methodologies do not explicitly account for the acceleration, top speed, headways, and climbing ability of trucks when assessing their impact on other modes.

4.1.2 Critique of How HCM Models Trucks

This section critiques the weaknesses of the current HCM methodology for modeling the effects of trucks on the traffic stream and facility performance. Several areas of concern have been identified, including underestimation of truck traffic in freight-dominated corridors; simplistic PCE conversions, which homogenize all trucks into a single truck type; and a lack of estimates of truck value of time and travel time reliability.

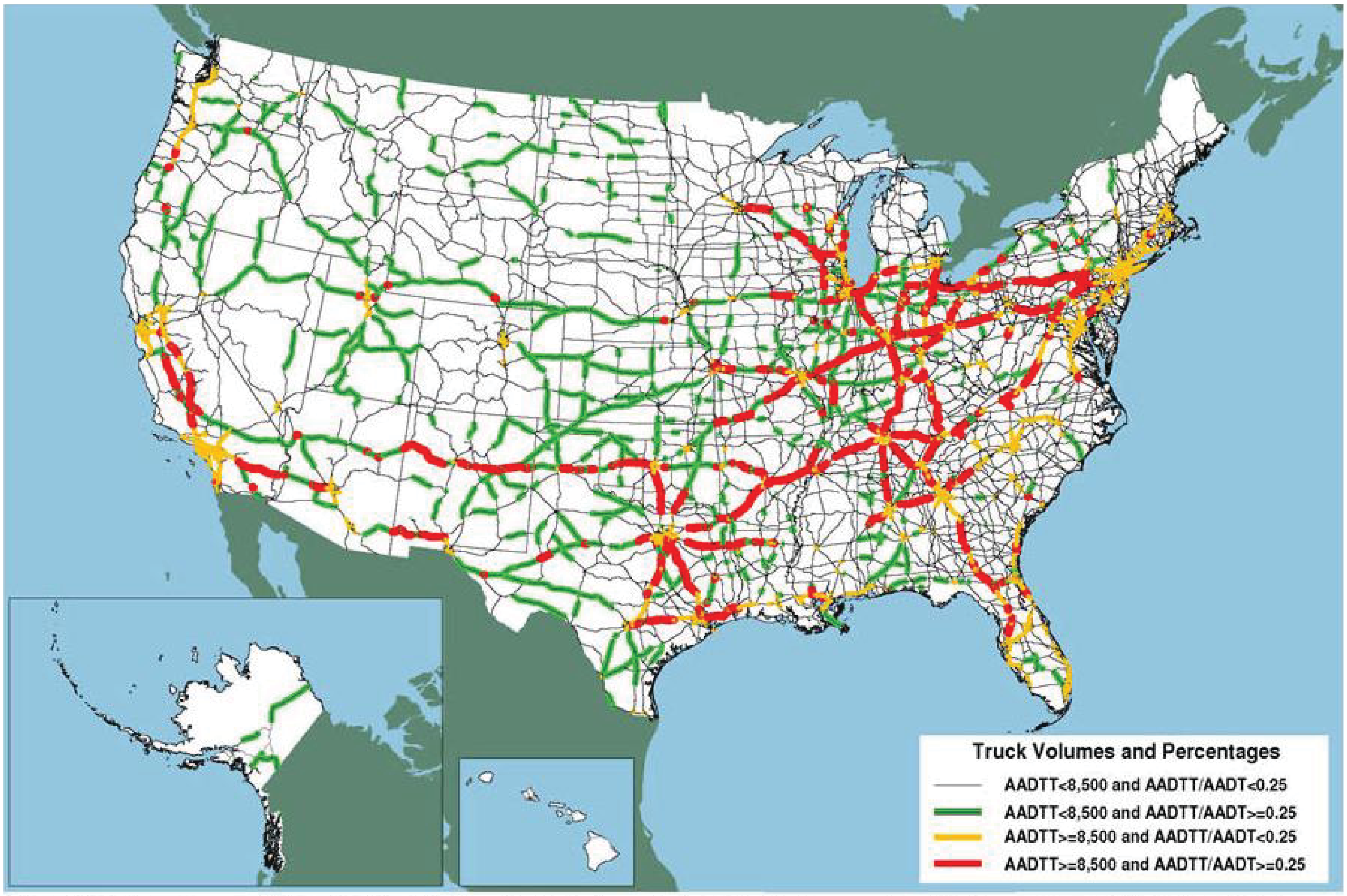
HCM Has Too Narrow of a Range for Truck Percentages

The HCM 2010 does not have a methodology to incorporate truck percentages higher than 25% on certain freeway segments that have a long grade (greater than 1.0 or 1.5 miles)—for example, the HCM can only handle truck percentages of 25% for positive grades (uphill) and 20% on negative grades (downhill). While 25% is a significant amount of trucks, there are many facilities that have truck percentages higher than this (see Exhibit 8). I-81 in Virginia, for example, has truck demands of between 40% and 50% (Rakha et al., 2007). This is not an isolated situation, with 6% of all counting stations in California (Caltrans, n.d.) and 3% of all counting stations in Virginia (Virginia DOT, 2008) recording truck volumes greater than 25%.

HCM PCE Conversions Too Simplistic

The HCM 2010 interrupted flow chapters lump trucks and buses together in computing the PCE values of heavy vehicles. The HCM approach is also independent of significant variables like the truck type and weight-to-horsepower ratio. Rakha et al. (2007) found that while PCEs are constant for low grades (under 2%), they decrease with increasing truck proportions. They suggested that different PCE values would be appropriate as truck proportions increased. This concept of PCE values needing to be related to proportion was further supported by Webster and Elefteriadou (Webster, 1999), who developed recommended PCE values for truck percentages of up to 60% using a weight-to-power ratio of 137.5 lb/hp. Their recommended PCEs were further adjusted to account for other weight-to-power ratios.

Exhibit 8. Percent trucks on National Highway System.



Note: AADTT is average annual daily truck traffic and includes all freight-hauling and other trucks with six or more tires. AADT is average annual daily traffic and includes all motor vehicles.
Source: U.S. Department of Transportation, Federal Highway Administration, Office of Freight Management and Operations, Freight Analysis Framework, version 3.1, 2010.
Source: FHWA Office of Freight Management and Operations, 2010.

Control delay at signalized intersections in the current HCM methodology does not consider the probability distribution of heavy vehicles within the queue; it only takes into account saturation flow rate using PCE factors. No provision is available to adjust start up loss or end gain with heavy vehicles in different queue positions. Ramsay et al. (2004) suggest this should be done in computing expected control delay. They propose incorporating a weighted average control delay considering vehicles in different queue positions.

The uninterrupted flow chapters currently assume a reduction in PCEs for facilities with a high percentage of trucks. This is presumably because the traffic stream becomes more homogeneous, which reduces the marginal impact of each heavy vehicle. Although not quantified in the HCM, state controls—such as the implementation of electronic toll collection and weigh-in-motion technology—surely have an impact on the performance of heavy vehicles in the traffic stream.

Elefteriadou et al. (2007) found that PCEs are highly sensitive to the weight-to-power ratio of heavy vehicles. Unfortunately, the HCM assumes a single truck type that was calibrated using a mix of trucks and buses with an average weight-to-horsepower (hp) ratio of between 125 and 150 lb/hp (see Chapter 11, HCM 2010). This does not account for the wide range of heavy vehicles on the road today—for example, both Middleton (2006) and Rakha et al. (2001) found a variety of trucks that have weight-to-power ratios greater than 150 lb/hp with values reaching as high as 300 lb/hp. It is also important to consider that effective horsepower can vary considerably with various weather, pavement, and vehicle conditions.

Primary Issues in Measuring Facility Performance Effects on Trucks

There are a number of issues with using the *Highway Capacity Manual* to estimate how facility performance will affect trucks as perceived by motor vehicle carriers and shippers. These issues include that

- Service measures used in the HCM are not relevant to carriers/shippers,
- No provision is made in the HCM for evaluating truck LOS separately, and
- The current HCM does not deal with travel time reliability for trucks.

Service Measures in the HCM Are Not Relevant to Carriers/Shippers

Service measures are a subset of performance measures, which are used to estimate LOS (letter grades A through F). With the exception of two-lane highways, the uninterrupted flow facility service measure is density. However, density is not a direct concern to shippers—even though density correlates to speed and delay (which is a concern for shippers), density itself is not a tangible service measure for movers of freight.

Service measures for two-lane highways vary by facility type: Class I facilities[2] use speed and percent time following, with Class II facilities relying solely on percent time following. Class III is the final type with its service measure based on the percentage of free-flow speed. Of the current measures, speed is the only service measure that may be particularly relevant to freight movers. The percentage of time that an automobile has to follow a truck is not a significant consideration for commercial goods movers.

Interrupted flow facilities such as urban streets with signalized intersections use service measures that do concern freight movers such as average control delay, but are not consistently sensitive enough to other measures like the number of stops on a route. Furthermore, these service measures are often quantified into LOS letter grades ranging from "A" to "F" that are based on the expert opinion of the authors of the chapters of the HCM (except Chapter 17: Urban Streets). Unfortunately, these perceptions to date have not reflected the perceptions of truck drivers, but rather are based on automobile drivers.

No Provision in the HCM for Evaluating Truck LOS Separately

The 2010 HCM does not have any methodology or LOS criteria specifically targeted to the needs of truck freight movers. Current HCM analysis methodologies convert trucks to equivalent passenger cars and then analyze the traffic stream as if it were all passenger cars. This approach results in a single traffic stream with averaged speeds, densities, and delays that does not fully consider the wide range of both vehicles and drivers on the roads today.

While knowing average performance measures is a useful tool in traditional operational analyses, it would still be useful to have a way of measuring truck LOS as its own measure. This is especially true given the economic importance of freight movement by truck. Unfortunately, there is no provision for evaluating truck LOS separately from automobile LOS in the HCM 2010. This lack of methodology becomes a critical gap when an agency is considering measures to restrict truck activity from certain facilities, lanes, or peak hours. The conventional automobile LOS analysis shows significant benefits for automobile drivers by using these measures, but there is no corresponding analysis of the disadvantages to trucks or the economic activity of the region.

[2] Two-lane highway "classes" are meant to address differences in purpose and driver expectations: Class I highways are connectors, where high speed is valued; Class II highways are recreational or scenic routes in which high speeds are not expected nor desired; Class III highways serve moderately developed areas (they may be portions of a Class I or Class II highway).

HCM 2010 Does Not Deal with Travel Time Reliability

A factor of great concern to movers of commercial goods is travel time reliability, which is especially important today because many businesses adhere to what is known as "just-in-time delivery," so they do not have to have large warehousing facilities. This delivery method requires coordination and the ability to accurately determine shipping time. The 2010 HCM does not provide any methodologies for determining travel time reliability, nor are there any measures provided that can be relevant to reliability.

There is major research being performed under the Strategic Highway Research Program (SHRP) in travel time reliability: SHRP2-L08 will add content to the HCM that deals with reliability and reliability performance measures. Incorporation of this research into the NCFRP Project 41 will be useful in developing truck LOS methodologies given that travel time reliability is such an important factor in freight movement.

4.1.3 Deficiencies of Current HCM Methodologies

Based on the results of the literature review, a review of international practice, the agencies survey, and the shippers/carriers survey, the deficiencies of the current HCM 2010 methodologies for evaluating the impacts of trucks on other highway users and the impacts of other highway users on trucks are as follows:

- The 2010 HCM PCE tables for specific grades on uninterrupted flow facilities stop at 25% trucks (e.g., HCM: Chapter 11). They should be extended to higher proportions of trucks in the traffic stream, perhaps to 50%.
- The 2010 HCM PCE tables for uninterrupted flow facilities and fixed single PCE values for interrupted flow facilities have undocumented built-in assumptions as to the distribution of weight to equivalent horsepower ratios (WEHPR) and lengths of trucks in the traffic stream. This limitation requires the original research to be repeated every few years as the vehicle fleet evolves. A methodology to predict PCE as a function of the distribution of WEHPRs and length of trucks in the traffic stream would facilitate maintenance and updating of future HCM PCE tables as the vehicle fleet changes.
- The current HCM heavy-vehicle categories of trucks, buses, and RVs needs to be subdivided for trucks into WEHPR and length subtypes to better match PCEs with actual vehicle mix and to produce more accurate estimates of the capacity effects of trucks.
- Urban Street Method does not have a factor for truck effects on base free-flow speed or running speeds between signals (HCM: Chapter 17).
- There are no truck-specific performance measures producible with the current HCM methodology. The HCM produces only average traffic stream delays and speeds without isolating the delays and speeds for trucks separately.
- The HCM does not identify a LOS measure specific to trucks.

4.1.4 Appropriate Uses of HCM for Truck Operations Analysis

Many public agencies have typically used HCM methods to compute volume/capacity ratios, average speed, average delay, and automobile LOS for the mixed automobile and truck traffic stream. The agencies then assume that average results for automobiles and trucks can then be used as a proxy for the conditions experienced by trucks in the traffic stream.

Where greater detail is needed, some agencies have used microsimulation analysis models to better model the interactions of trucks with each other and the passenger car traffic stream and report average traffic stream performance. Relatively little has been done to tease out truck-specific performance measures from the output of conventional HCM and microsimulation models.

In economic analyses used to prioritize projects for investments, separate values of time (VOT) have been assigned to truck movements within the traffic stream. However, due to the lack of truck-specific performance measures available from conventional modeling methods, truck-specific VOTs have been applied to mixed traffic stream speeds and delays.

The accuracy of the benefit/cost analyses currently used to prioritize transportation system investments can be significantly improved if the correct truck-specific performance measures were available: average truck speed, average truck delay, and reliability.

The VOT for truck movements used to compute the economic value to the region of transportation investments would also be greatly improved if it could be specified in terms of a distribution rather than a single average value. A framework that could provide truck average speed, delay, and reliability according to the specific VOT for each subtype of truck movement would greatly improve the accuracy of the economic analyses used to prioritize transportation system investments.

Truck LOS letter grades (i.e., A through F) keyed to truck delays, truck speeds, reliability, and the VOT for the specific truck movements being evaluated would also greatly facilitate the identification of freight movement problem spots in the highway network, comparison of alternative improvements, the determination of significant impacts, and the determination of acceptable and unacceptable performance.

4.1.5 Recent Research on Truck Level of Service

While separate truck LOS methodologies have not been incorporated into the HCM to date, there have been a number of research efforts that have been trying to deal with this issue. While these research efforts are an excellent foundation, much more is still needed before a working truck LOS methodology can be incorporated into the HCM.

One issue is that these prior research efforts have surveyed primarily truck drivers rather than carriers or shippers. One can see the bias in the results caused by focusing on drivers rather than carriers and shippers. The truck driver responses during these interviews are more concerned about comfort and convenience of the trip rather than trip time or reliability.

Hostovsky and Hall

Hostovsky and Hall (2003) conducted a focus group study of truck drivers at the annual convention of the Ontario Trucking Association (OTA) in Canada. Members of the OTA Road Knights Team were used for the focus group. The OTA Road Knights Team is a group of 10 professional transport drivers with first-class driving records who make presentations on how car and truck drivers can safely share the road.

The Road Knights Team consists of only tractor-trailer drivers and does not include drivers of straight trucks, dump trucks, buses, and other heavy vehicles. The goods carried by the OTA participants include office products (from Toronto to New York City), general freight around Toronto and to the United States from Ontario, and chemical tankers.

Two simple, open-ended questions were used to start the focus group:

1. When driving your truck, what makes for a good trip on a freeway for you?
2. When driving your truck, what makes for a bad trip on a freeway for you?

The participant responses were grouped under freeway conditions, traffic conditions, attitudes of other drivers, safety, and aggressive driver behavior. Travel time (or speed), traffic density (or maneuverability), and traffic flow were three major variables that were all mentioned with regard to freeway conditions quality of service.

For freeway conditions, drivers were worried about factors such as road marking in construction zones, narrower lanes, snow being cleared promptly, and evenness of pavements. Drivers tend to prefer the middle lanes, which offer the "smoothest ride." For traffic conditions, a key issue mentioned repeatedly was steady traffic flow. Due to the longer time required for trucks to accelerate and decelerate (compared with automobiles) drivers have a very negative perception of stop-and-go traffic. Drivers mentioned that "Traffic moving steadily within an acceptable range" was the most important factor to them rather than speed. This does not necessarily imply drivers do not value speed, but may rather reflect an implicit understanding from experience (of the drivers) that steady speed is more likely to result in a higher overall speed than stop-and-go traffic.

Drivers point out that congestion due to construction, road maintenance, and accidents is very problematic for their operations—for example, while closures of major freeways at night for maintenance and construction do not bother commuters, it does affect truckers because it is considered "premium truck traffic time" where they can travel without interference from automobiles. The authors concluded that "truckers are concerned about travel times (or average speed) and about maneuverability, but there was a stronger consensus on the importance of what they termed flow or moving at a steady speed within an acceptable range."

Another issue mentioned is attitudes toward other road users. Here truck drivers' general perception was that they were more professional and consistent in their driving behavior and habits than were other road users. Their perception was that the driving behavior of other non-truck drivers (lane changing, signaling, etc.) was inconsistent and disconcerting. This behavior negatively impacted their perception of a trip. Safety was a recurring theme throughout the focus study that included driving behavior of other road users, maintenance of safe driving conditions (during winter), clearance of snow, rubbernecking at accident scenes, and so forth.

The key finding of the study was that the very nature of the tractor-trailers (large, heavy vehicles with stiff suspensions that require long braking distances and more time to accelerate) makes them place significance on LOS variables other than traffic density, which is used by engineers and planners in the HCM. It is not traffic density that mattered to them—it was traffic "flow," which means what mattered most to this particular group of participants was a "comfortable operating range of highway speeds that does not require much braking and gear changes related to acceleration. Most of the truckers do not mind reduced freeways speeds as long as the traffic is flowing steadily." The primary concern of urban freeway commuters was travel time, especially reduced time in light of frequent stops. Therefore, it can be concluded that truckers do think of time for their ability to deliver cargo, but they prefer a longer predictable time to having an unsteady traffic flow when perceiving their quality of service.

Washburn

A preliminary methodology for assessing truck LOS only for basic freeway segments was developed by Washburn in 2002. This methodology was developed without benefit of surveys of motor vehicle carriers, shippers, or even truck drivers. The methodology proceeds upon the presumption that maneuverability is an important factor for truck drivers (Washburn, 2002).

The methodology is based on a function of the ratio of percent of free-flow speed (FFS) of trucks to percent of FFS of passenger cars and is referred to as the "Relative Maneuverability Index," or RMI. It can be expressed as

$$RMI = \frac{Percent\ FFS_{trucks}}{Percent\ FFS_{pcars}} \qquad \text{Equation 2}$$

The intent of the RMI was to capture the effect in which truck drivers are not able to change lanes at the same frequency as cars do at various density levels. Thus, trucks experience lower average speeds than cars because they cannot perform as many discretionary lane changes to maintain their desired speed. This research did not perform measurements of this presumed preference of drivers to change lanes to maintain desired speed nor did this research attempt to measure or capture the perceptions of motor vehicle carriers or shippers.

Conceptually, RMI approaches a value of one under both free flow and ideal geometric conditions when most cars and trucks are travelling at their desired (albeit different) FFS. It would also approach 1.0 under stop-and-go congested conditions when very few cars and trucks are able to maintain their FFS. The RMI would drop below one between these two extremes.

A surrogate value for the numerator and denominator is the ratio of the average speed to FFS by vehicle class. A further extension of this concept is the ability to estimate a truck density equivalent for truck LOS estimation purposes with a known or estimated RMI. This estimation is accomplished using the following relationship:

$$Density_{trucks} = \frac{Density_{pcars}}{RMI} \qquad \text{Equation 3}$$

The numerator in Equation 3 is taken as the computed HCM LOS measure for basic freeway segments, while the RMI in the denominator is assumed or estimated.

The approach used in this research was to calibrate/develop speed prediction models for both trucks (three types) and passenger cars using a microscopic freeway simulation model (FREESIM). Other field based approaches were considered and discarded due to the complexity and cost of flow and speed data collection by vehicle class. The simulation model was first calibrated against sensor data extracted on the I-4 freeway in Orlando, FL. These data were supplemented with surveillance video data to retrieve actual counts of the various truck classes.

Once the simulation model produced reasonable comparisons to the field data, it was used to develop statistical speed models for a representative basic freeway segment for four classes of vehicles (one passenger car and three truck categories) by varying factors for total volume (or volume per lane), percent trucks, road grade, and number of truck lane restrictions. Thus, each of the four speed models takes the form

$$S(\text{class } i) = f(\text{intercept, volume, grade, percent trucks, restricted lanes, interaction terms}) \qquad \text{Equation 4}$$

The intercept term therefore represents the FFS for the subject vehicle class. Applying the models by class means the RMI, truck density, and LOS can be computed.

This study explored the development of a method to assess LOS for trucks based on a maneuverability measure, which was a function of relative percentages of FFS between trucks and passenger cars. There is some work needed to be done, such as revising the model to use a variable for the segment entering average speed of the vehicle class instead of using a base FFS. It would also be desirable to perform field verification of base FFS of trucks relative to passenger cars to serve as validation for the values that result from the simulation model.

Washburn and Ko

Washburn and Ko (2007; also see Ko, Washburn, and McLeod, 2009) conducted opinion surveys of 459 truck drivers and 38 carrier managers to identify the roadway, traffic, and other highway-related factors most important to them. The effects of truck regulations were explicitly excluded. They attempted to survey a cross section of driver types representative of different carrier and equipment types.

They found that drivers and carriers tended to place greater emphasis on different aspects of the highway experience. Drivers placed greatest importance on the quality of the ride and ease of driving (pavement smoothness, fewer maneuvers required, and ease of maneuvers). Carriers placed greatest emphasis on speed and travel time reliability.

Based on the combined results from drivers and carriers, the authors recommended the following key measures of LOS for evaluating truck performance on a facility:

- Freeways—speed variance and pavement quality;
- Two-lane highways—percent time being followed, percent time spent following, travel lane and shoulder widths, and pavement quality; and
- Urban streets—ease of turning maneuvers, speed variance, traffic density, and pavement quality.

Note that speed variance, in this case, refers to the "ease of maintaining a consistent speed" over the length of a trip and not the variation in average trip speed from trip to trip, which reflects to a certain extent the psychological comfort of a trip. It is essentially a measure of the amount and frequency of accelerations and decelerations during the trip.

Even though motor vehicle carriers were surveyed, none of the recommended truck LOS measures dealt with speed and travel time reliability, which were the primary concerns of shippers and carriers. Instead, the recommended LOS measures of comfort and convenience focus on the needs and perspectives of truck drivers.

4.2 International Practice

A scan of the international literature review found that several countries are still in the process of developing their highway capacity manuals. Significant differences in traffic laws of individual countries limit the transferability of procedures and PCEs adopted by other countries. The general finding from the literature scan is that most capacity analysis manuals from other countries generally follow the HCM 2010 concept of converting trucks to PCEs and then computing capacity and performance for the equivalent passenger car stream.

None of the international manuals reviewed to date provide performance measures or methodologies for measuring or predicting LOS from the point of view of truck shippers or carriers. Capacity analysis manuals and relevant research from the following countries were reviewed:

- Germany,
- The United Kingdom,
- Canada,
- China,
- Indonesia,
- Australia,
- Brazil,
- Japan,
- India,
- Thailand, and
- Singapore.

4.2.1 Germany

In Germany, heavy-vehicle percentages in traffic stream are used as parameters describing the influence of trucks on both freeways and rural highways. All vehicles with a maximum

Exhibit 9. German motorway capacities under ideal conditions.*

Truck percentage	6-lane motorways	4-lane motorways	
		Metropolitan	Long distance
0%	1820	2075	1815
5%	1780	2010	1790
10%	1730	1945	1765
15%	1690	1875	1740

*Capacities in vehicles per hour per lane; adapted from Wu, 1998.

weight above 3.5 metric tons are considered as heavy vehicles (the maximum allowable weight is 40 metric tons, width is 2.6 m, and length is 18.75 m with some exceptions).

Differences between German and U.S. traffic laws suggest that German PCEs and truck analysis methods may not be directly transferable to the United States. The maximum allowable speed for trucks in Germany is 80 km/h (49 mph), however, it is not strictly enforced. On the other hand, the maximum speed of passenger cars is 140 km/h (85 mph) on a level freeway. In general, prohibition of overtaking by trucks is implemented in German freeway networks. Right-hand overtaking by any vehicle of any other is prohibited in Germany, a rule that is generally obeyed.

As a result, trucks and cars in freeways are segregated. These circumstances have resulted in trucks running on the far right lane nearly all the time. Trucks use the left or middle lane only for overtaking. Trucks are not allowed outside of the two right-hand lanes on a freeway. It is mandatory in Germany that trucks keep a distance of 50 m (150 ft) between them for safety. Occasionally, on some of the major freight-hauling freeways, long "freight-truck" queues are observed in the right lane. These moving truck queues create problems for car drivers exiting or entering the freeway at junctions.

Currently, when computing performance measures, passenger car speed is the key input. In computing roadway performance measures, there is an implicit assumption that increasing traffic volumes adversely impact trucks and automobiles in the same manner and to the same degree. Road gradient, different speed-flow characteristics, and different capacities are also taken into account while analyzing performance measures.[3]

In 1994, the first draft of a German *Highway Capacity Manual* (German HCM) was presented on behalf of the Federal Minister of Transport to improve the practical applications of traffic engineering theories (Wu, 1998). The theoretical capacity on German motorways under ideal conditions (light and dry) is shown in Exhibit 9.

Geistefeldt (2009) proposed a new empirical method for estimating PCEs for heavy vehicles on freeways. The proposed approach is based on the concept of stochastic capacities, illustrated by the capacity distribution functions. Capacity distribution functions were created using 5-min interval traffic counts from German freeways with varying geometric parameters. The empirical PCE estimation and the parameters of the corresponding capacity distribution functions vary from 1.3 to 2.6. The estimated PCEs tend to decrease with an increasing number of lanes.

A comparative study was performed to compare saturation flow rate as presented in the German HCM. The study site was in the City of Dresden; the saturation flow rates with varying grades and heavy-vehicle combinations were compared (Boltze, 2006). The basic capacity is 2,000 vehicles per hour. The influence of heavy vehicles and grade on the saturation flow is shown in Exhibit 10.

---

[3] By way of comparison, the United States' HCM 2010 defines a heavy vehicle as a vehicle with more than four wheels on the ground during normal operations.

Exhibit 10. Dresden and German HCM saturation flow rates.*

	0% Heavy Vehicles		10% HV		20% HV		30% HV	
Grade	German HCM	Dresden	German HCM	Dresden	German HCM	Dresden	German HCM	Dresden
0%	2000	2000	1860	1800	1540	1600	1380	1300
2.5%	1835	2000	1710	1800	1410	1600	1265	1300
3.0%	1800	1950	1680	1750	1385	1550	1240	1250
4.0%	1750	1850	1630	1600	1345	1450	1205	1200
5.0%	1700	1650	1585	1350	1310	1250	1170	1150

*Entries are saturation flow rates in vehicles per lane per hour of green for signalized intersections. German HCM is German *Highway Capacity Manual*. Source: Boltze, 2006.

Brilon and Bressler (2004) analyzed traffic flow characteristics on freeway upgrades in Germany. They used all external influences, degree of gradient, and length of upgrade together with traffic flow parameters such as volume or proportion of heavy vehicles through specific parameters. Based on this analysis, they found that capacity solely depends on the degree of gradient but is not influenced by gradient length. However, travel speed is significantly influenced by the degree of gradient and the length of the grade (up to $L \leq 4000$ m) as well as by the proportion of trucks.

4.2.2 United Kingdom

Traffic Capacity on Urban Roads (Department of Transport, Highways Agency, n.d.) provides capacity look-up tables for various types of roads according to the proportion (up to 15%) of heavy vehicles on the road. The recommended capacity adjustments for higher proportions (the heavy-vehicle percentage in a one way flow exceeds 15%) of heavy vehicles are shown in Exhibit 11. In the United Kingdom, the motorway speed limit is 60 mph or less within a built-up area. For urban all-purpose roads, the speed limit is either 40 mph or less for a single carriageway or 60 mph or less for a dual carriageway.

4.2.3 Canada

The Canadian *Capacity Guide for Signalized Intersections* (Canadian Institute of Transportation Engineers, 2008) incorporates heavy vehicles for design of traffic signals and analysis. Heavy vehicles are included as a passenger car unit equivalent, which is discussed in the following section.

Passenger Car Unit Equivalent in Flow

The Canadian *Capacity Guide* focuses on the movement of traffic flow units including trucks such as cars, transit vehicles, cyclists, and pedestrians at signalized intersections. Vehicular traffic flow is commonly expressed as a homogeneous entity by converting the individual vehicle class into passenger car units (PCUs). Three types of trucks are listed in the Canadian *Capacity Guide*. Exhibit 12 illustrates the truck classification and corresponding PCU.

Exhibit 11. Reduction in flow due to heavy vehicles.

Heavy-vehicle %	Total reduction in flow level (veh/h)		
	UM and UAP dual carriageway road	Single carriageway UAP road having width of 10 m or wider	Single carriageway UAP road having width less than 10 m
	Per lane	Per carriageway	Per carriageway
15–20%	100	100	150
20–25%	150	150	225

Notes: UM = Urban motorway; UAP = Urban all-purpose road. Source: Department of Transport, Highways Agency, n.d.

Exhibit 12. Canadian passenger car unit equivalents—signalized intersections.

Truck types	Passenger car unit equivalents (pcu/veh)
Single unit trucks	1.5
Multi-unit trucks	2.5
Multi-unit trucks heavily loaded	3.5

Source: Canadian Institute of Transportation Engineers, 2008.

Saturation Flow Adjustment Factors

The Canadian *Capacity Guide* suggests a number of adjustment factors to adjust the basic saturation flow values for heavy vehicles including other adjustment factors in the absence of directly measured saturation flows at the analyzed intersection. The adjusted saturation flow depends on the basic saturation flow and is a function of the applicable adjustment factors:

$$S_{\text{adj}} = S_{\text{basic}} f(F_{\text{adj}}) \qquad \text{Equation 5}$$

where

S_{adj} = adjusted saturation flow (pcu/h),
S_{basic} = basic saturation flow (pcu/h),
$f(F_{\text{adj}})$ = adjustment functions, and
F_{adj} = individual adjustment factors.

Truck Size and Weight in Canada

The truck size and weight regulations in the Canadian provinces in the 1960s were similar to those in the U.S. states. The detailed specifications were developed for tractor-semitrailers from 3 to 6 axles and A-, B-, and C-trains from 5 to 8 axles for interprovincial highway transportation. Canadian provinces and territories have the authority to set, monitor, and enforce truck size and weight regulations. Woodrooffe et al. (2011) suggested that the process of implementation was advancing slowly. The delay was due to public concern in Ontario with an increase in semitrailer length and overall length for doubles, which restricted full implementation in the six eastern provinces for five years. Researchers argued that there was national agreement among stakeholders that Canadian size and weight regulations were inconsistent and outdated, which contributed to cross country transport inefficiencies (Abdelgawad et al., 2010).

Exclusive Truck Facilities in Canada

Roorda et al. (2010) analyzed exclusive truck facilities in the Greater Toronto Area (GTA). The research was motivated from studies on truck facilities being conducted in many U.S. states (Florida, Texas, Virginia, etc.). Travel demand on the 400-series freeway is modeled and calibrated in detail to reflect observed freeway traffic volume.

Two scenarios were evaluated. In one scenario, the conversion of one lane in Highway 401 in each direction into an exclusive truck lane resulted in stable overall freeway demand for passenger cars and light truck trips and an increase in demand for medium and heavy truck trips by 5% to 15%. The scenario also resulted in reduced passenger car and light truck capacity and increased medium and heavy truck capacity on Highway 401. The resulting effect was approximately stable freeway demand for passenger cars and light trucks and a significant increase in freeway demand for medium and heavy trucks over the base case.

In the second scenario, construction of an exclusive truck highway in a hydro corridor across the GTA resulted in a 3% to 7% increase in passenger car/light truck trips on the freeway and an 8% to 13% increase in medium and heavy truck trips.

Exhibit 13. Passenger car equivalents for road links studied in China.

Road type/ total both directions*	Terrain type	Traffic flow (veh/h)	PCEs (PCE for LV = 1.0)					
			MV	MHV	LHV	TC	TRA	MC2
4/2 UD + D (CW = 13–16 m)	Flat	0	1.3	1.4	1.6	2.2	3.2	0.5
		2500	1.4	1.5	1.8	2.4	3.5	0.5
		5000	1.2	1.2	1.4	2.0	2.5	0.3
	Rolling	0	1.7	1.8	2.5	3.4	3.8	0.5
		2100	1.9	2.0	2.5	3.4	4.2	0.5
		4200	1.8	1.5	1.8	2.4	3.4	0.3
	Hilly	0	1.8	2.0	3.1	4.2	4.4	0.3
		1750	2.0	2.3	3.1	4.2	4.9	0.4
		3500	1.9	1.7	2.4	3.4	3.9	0.3

*Notes: UD = undivided; D = divided; CW = carriageway (roadway width).

In the same study corridor, Abdelgawad et al. (2010) conducted a simulation study for exclusive truck lanes. Researchers evaluated two alternatives: in the first, addition of four-lane truck facilities resulted in greater travel time improvements for trucks, which resulted in the reduction of freeway average travel speeds in the network for both A.M. and P.M. peak hours. In the second alternative, conversion of a freeway lane to an exclusive truck lane on Highway 401 resulted in increased congestion for passenger cars, but improved travel speeds for trucks. Both of these scenarios show truck facility usage ranges from 100 to 800 trucks per hour per direction.

4.2.4 China

A comprehensive highway capacity study was conducted from 1995 to 1999 with the purpose to develop draft capacity guidelines for roads and major intersections outside of urban areas (Bang and Heshen, 2000). Field data were collected at 144 road links and at 19 major intersections outside of urban areas. The project was intended to support central efforts towards the development of a complete Chinese *Highway Capacity Manual.* The following average traffic composition was recorded from the surveyed sites:

- MC2—two-axle motorcycles 4%;
- MV—mini-vehicles (3 and 4 axles) 10%;
- LV—light vehicles (cars, vans, etc.) 27%;
- MHV—medium heavy vehicles 25%;
- LHV—large heavy vehicles 21%;
- TC—truck combinations 8%; and
- TRA—farm tractors 5%.

The corresponding PCE for these types of vehicles is shown in Exhibit 13. The recommended base FFSs depend on road, terrain, and vehicle types and are shown in Exhibit 14.

Exhibit 14. Base free-flow speed for interurban and township road in China.

Road type/ both directions	Terrain type	Base free-flow speed (km/h)					
		LV	MV	MHV	LHV	TC	TRA
Motorway	Flat	90	70	70	65	60	—
	Rolling/ hilly	80	60	60	52	50	—
Multilane road >13 m	Flat	70	55	62	62	54	25
	Rolling	65	50	57	55	47	23
	Hilly	60	45	51	48	39	20

Source: Bang and Heshen, 2000.

4.2.5 Indonesia

The Indonesian highway agency realized that the existing capacity manuals from developed countries could not be successfully implemented in Indonesia because Indonesian traffic characteristics differ from those of developed countries (Indonesian Directorate General of Highways, 1993). Thus, data collection was performed at a total of 147 sites in 16 cities in Indonesia to develop capacity parameters appropriate for Indonesia.

Based on this data collection effort, the following PCEs were identified. For signalized intersection analysis, a heavy-vehicle factor of 1.3 is used to convert to PCUs. For urban roads, the default PCU value of 1.3 is used for heavy vehicles. If there are a lot of heavy vehicles, a PCU of 2.0 could be used. Heavy vehicles are classified as buses, two-axle trucks, three-axle trucks, and truck combinations.

Heavy vehicles classifications include the following (Indonesian Directorate General of Highways, 1995):

- Medium heavy vehicle (MHV): two-axle motor vehicles with an axle spacing of 3.5 to 5.0 m, including buses and two-axle trucks with six wheels;
- Large trucks (LT): three-axle trucks and truck combinations with axle spacing from first to second axle of <3.5 m; and
- Large bus (LB): two- or three-axle buses with an axle spacing 5.0 to 6.0 m.

For interurban roads and motorways, capacity is measured in light vehicle units (LVUs). Two sets of LVU values are used with different criteria for equivalency (see Exhibit 15):

- Speed-based LVU values are based on the relative impact on light vehicle speed due to different types of vehicles in the traffic stream; and
- Capacity-based LVU values are based on the relative impact on capacity due to different vehicle types.

The *Indonesian Highway Capacity Manual* suggests that the FFS for a passenger car is typically 10% to 15% higher than that for other types of light vehicles. The actual capacity is adjusted from ideal capacity by incorporating a road width adjustment factor, a directional split adjustment factor, a motorcycle traffic adjustment factor, and a side friction adjustment factor. The calculation procedures given in the manual are in some cases similar to the U.S. HCM; users are advised to use values for Indonesian conditions as appropriate.

For motorways, the Indonesian HCM recommends a FFS of 85 km/h (52 mph) and a base capacity of 2,300 LVUs/h/l, respectively, for a four-lane divided motorway in flat terrain.

Indonesia does not use the U.S. HCM LOS concept; therefore, speed and degree of saturation are used in the Indonesian HCM. Speeds are much lower in Indonesia than in the United States for a given degree of saturation (flow/capacity = Q/C) (Indonesian Directorate General of Highways, 1993).

Exhibit 15. Light vehicle units conversion in Indonesian HCM.

Terrain/Road Type	LVU (speed)			LVU (capacity)		
	MHV	LB	LT	MHV	LB	LT
Flat terrain/Divided road	1.5	1.0	3.2	1.2	1.5	2.0
Flat terrain/Undivided road	1.5	1.2	2.7	1.2	1.5	2.0
Rolling terrain/All road types	2.0	1.3	4.0	1.3	1.7	2.5
Hilly terrain/All road types	3.5	1.5	5.5	1.5	2.0	3.0

Source: Indonesian Directorate General of Highways, 1995.

4.2.6 Australia

Austroads published *Guide to Traffic Management* for traffic studies and analysis. The guide provides guidance on traffic analysis for uninterrupted and interrupted flow for various types of intersections. Different factors affecting capacity and LOS due to roadway condition, traffic composition, and so forth are also presented in the guide (Austroads, n.d.).

The document defines “truck” as a vehicle with more than four single tires and involved primarily in the transport of goods and services. It utilizes the HCM 2000 methodologies for calculating capacity, delay, and LOS on transportation facilities. A suggestion is made in the document that when using the HCM 2000 procedures, the vehicle equivalency factors should be adjusted to reflect the characteristics of Australian trucks. However, there is no evidence in the document that provides guidelines on appropriate values for vehicle equivalency of Australian trucks that should be used in the analysis.

4.2.7 Brazil

A study was conducted in Brazil to estimate truck PCEs for divided multilane highways (Cunha and Setti, 2011). In Brazil, trucks represent a high proportion of highway traffic and they are longer, heavier, and have smaller engines than the trucks used in the development of the HCM 2000. Truck characteristics (power, weight, etc.) were observed at several weigh stations on multilane highways. A microscopic traffic simulation software, CORSIM’s heavy-vehicle performance and car-following models were recalibrated using a genetic algorithm with truck performance data and traffic data collected on a divided multilane highway. The recalibrated CORSIM was then used to derive new PCEs. PCE tables for specific grades and for extended segments were created to replace those used in the HCM 2000. The results show the need for development of a Brazilian HCM. They suggested that the use of the PCEs found in this study may improve LOS estimates rather than to adapt from the HCM to Brazil. Demarchi and Setti (2003) used two types of trucks in the analysis for illustration purposes with varying mass-to-power and lengths. The results indicate that the errors in the estimation of equivalent flow rates are negligible for densities less than 10 veh/(km-lane), but increase significantly with the increase in density. The derivation of an aggregate PCE could avoid this problem.

4.2.8 Japan

The latest trucking research in Japan is concerned with futuristic automated truck lanes, which promise to reduce congestion and increase safety. For purposes of analyzing such lanes, Morikawa, Miwa, and Sun (2011) studied the New Tomei Expressway and obtained—through maximum likelihood estimation—a PCE value of 1.73.

Rahman, Okura, and Nakamura (2003) suggested a method for estimating PCE in Japan for large vehicles at signalized intersections based on increased delay caused by the large vehicles. Researchers found that for the same percentage of heavy vehicles, the PCE value varies considerably with the position of large vehicles in the queue. In this study, a queue length of 8 to 17 vehicles was used to develop PCE values at signalized intersections.

4.2.9 India

The Central Road Research Institute (Indian Central Road Research Institute, 1988) adopted a linear regression analysis technique for determining PCE for different classes of vehicles, including trucks. Aggarwal (2011) developed a fuzzy based model for the estimation of PCE value for trucks based on inputs such as pavement width, shoulder condition, directional split,

Exhibit 16. Thailand PCEs.

Vehicle		PCE
Motorcycle		0.25
Passenger car		1.00
Taxi	4-wheel	1.00
	Tuk-Tuk (3-wheel)	0.75
Bus	Light	1.25
	Medium	1.50
	Heavy	2.00
Truck	4-wheel	1.75
	6-wheel	1.75
	10-wheel	2.00
	Articulated	3.00

Source: Mathetharan, 1997.

and speed of the traffic. Most of the research has provided significant insight about mixed traffic operation in India, but has recommended only static PCE values for trucks and other vehicle categories for different roadways and control conditions.

4.2.10 Thailand

The wide variety of vehicles in Thai roads requires a comprehensive approach to PCE. Exhibit 16 is an adaptation of a table published by Mathetharan (1997), which is still used in Thailand to homogenize traffic streams.

Minh and Sano (2003) studied the influence of motorcycles on saturation flow rates in Hanoi and Bangkok and arrived at a PCE of 0.24 and 0.18, respectively. While motorcycle PCEs may not be of interest for this project, the methods used in this project—plotting the proportion of motorcycles against the saturation flow rate—appear to be representative of Thai PCE research.

Another study conducted in Thailand suggested that the overall effect on the capacity with the prevailing proportion of large-sized vehicles resulted in reduction in capacity on the order of 15%. PCEs for medium- and large-sized vehicles are obtained as 1.0 and 1.5 respectively (Tanaboriboon and Aryal, 1990).

4.2.11 Singapore

A comprehensive 2-year study of truck traffic at 219 Singaporean sites was conducted by Fwa, Ang, and Goh (1996). It was found that the time distribution of truck travel varies greatly among the five roadway classes (i.e., expressways, arterials, collectors, industrial roads, and local roads).

In a similar study, Fan (1990) suggested PCE values of 1.3, 2.6, and 2.7 for light trucks, heavy trucks, and buses, respectively, for Singapore expressways. These PCE values are higher than those recommended for use in the United States.

4.3 Conclusions of Literature Review

Review of international literature and practice found that most countries use PCEs like the U.S. HCM to convert trucks in the traffic stream into the equivalent number of passenger cars before computing capacity and speed. Unlike the U.S. HCM—which uses a single class of trucks—China, Indonesia, Singapore, Thailand, and Canada subdivide trucks into three or four subtypes.

U.S. research suggests that truck PCEs used to compute saturation flow rates at signalized intersections should vary by truck size (i.e., the number of axles). The U.S. HCM currently uses just a single truck class (plus separate classes for buses and RVs). Japanese research found that the PCE effect of a truck on saturation flow rates also varies by the position of the truck in the signal queue. Similar findings were reported in U.S. research (Washburn and Cruz-Casas, 2010).

Chinese, Brazilian, Canadian, Indonesian, and U.S. research all confirm that PCEs vary by weight to equivalent horsepower ratio (WEHPR). U.S. research confirms the HCM PCE tables, which show that the effects of trucks decrease as trucks make up a larger proportion of traffic stream. This same research, however, suggests that HCM tables should be extended above 25% trucks in the traffic stream. U.S. research suggests that vehicle length (as opposed to WEHPR) affects truck PCEs for freeways on level sections.

German research has identified differing effects of different percent of heavy vehicles on signal saturation flow rates as a function of approach grade. For freeways, German research has found that the PCEs of heavy vehicles decrease with increasing number of lanes.

Indian research found that PCEs increased 20% over a 14-year period in that country, perhaps due to the evolution of the vehicle mix and vehicle WEHPRs, which suggests that the U.S. HCM PCE tables should be specifically tied to a specific distribution of truck subtypes (WEHPRs) and updated regularly.

This literature research on international truck analysis did not identify any LOS analysis performance measures or procedures designed to specifically represent the perspectives of truck shippers or carriers.

All international capacity manuals do provide PCE parameters to convert trucks to equivalent PCUs before estimating the equivalent capacity and speed for the passenger equivalent traffic stream. The differences in traffic laws among countries and the horsepower to weight ratios of trucks in other countries suggest that actual PCE values cannot be transferred directly to U.S. practice.

Several countries provide additional gradations of truck types beyond the simplistic U.S. HCM method of truck, bus, and RV. These classification schemes may provide some useful ideas for an augmented U.S. HCM truck classification scheme.

SECTION 5

Recommended HCM Truck Classification Scheme

This section reviews the current national and statewide truck classification schemes and recommends an appropriate classification scheme for use in the analysis of the effects of trucks on other modes and the effects of other modes on the quality of service experienced by trucks on the highways.

Two characteristics of trucks are of primary importance when predicting the effect of trucks on facility performance and vice versa: truck length and the ratio of weight to power.[4] There are numerous truck classification schemes currently in use in the United States, and each was developed for a different purpose. The intent of this section is to present a method for transforming these different classifications into a set of classifications that can best be used in the *Highway Capacity Manual* (HCM) to predict truck performance. Exhibit 17 shows the steps that may be required to transform one or more of the existing national classification schemes into a scheme useful for HCM analysis.

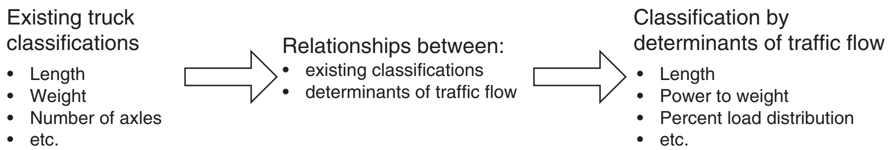
Another issue relevant to the objectives of NCFRP Project 41 is to provide guidance on analyzing highway performance measures that are of direct relevance to shippers. The main thrust of HCM analyses is on *average* peak period operational measures for a given set of conditions; however, as will be discussed later, reliability is a key concern for many shippers. This is particularly true of those involved with just-in-time inventories or high time value cargos.

The rest of Section 5 discusses the following topics:

- **Overview of existing truck classification schemes.** This provides a review of current national classification schemes and some variations on these.
- **Determinants of truck performance in the traffic stream.** Truck characteristics that affect their performance in the traffic stream are often not directly related to the bases for most-current truck classification schemes. This section briefly reviews those characteristics that are most relevant to truck performance, and discusses how they might be related to existing classification schemes.
- **Automated truck counting and classification considerations.** Automated truck counting and classification data are becoming increasingly more available through technologies such as weigh-in-motion (WIM) and increased sampling coverage for Highway Performance Monitoring Systems (HPMS). This section discusses those classifications and their relevance to the needs of NCFRP Project 41.
- **Perspectives of the trucking industry.** Freight haulers and their customers have somewhat different perspectives on relevance of highway performance characteristics to their needs. For example, reliability is highly valued where shipping is for just-in-time inventories.
- **Recommended HCM classification scheme.** This section provides the thinking of the research team on how to adapt existing classification schemes to meet the needs of NCFRP Project 41 and, ultimately, the HCM. This thinking was tested with available data as the research progresses.

[4] The value of time for the load carried, facility geometry, and traffic congestion on the facility are also critical factors, but these are not characteristics of the truck itself, per se.

Exhibit 17. Transforming existing classifications to flow-determining classifications.



5.1 Existing National Truck Classification Schemes

There are four basic national truck classification schemes and several variations on these schemes (see Exhibit 18). These four major classification schemes differ according to their purpose:

1. The national **NHTSA truck classification scheme** is based on gross vehicle weight rating.
2. **The FHWA truck classification scheme** is based on the number of axles, their configuration (tandem or single), and the number of trailers. It is designed to facilitate truck classification at weigh stations. The number of axles (in combination with loaded weight) is useful for pavement design.
3. **The STAA (Surface Transportation Assistance Act of 1982) truck classification scheme** identifies a new category of trucks eligible to operate on the National Network. However, they are subject to local controls and prohibitions when off of the National Network. These trucks are generally exceptionally long, so the STAA scheme is primarily based on length. The lengths determine the turning radii for the truck-trailer combinations.
4. **The AASHTO truck classification scheme** is based on the wheel base, the distance between the front wheels or trailer king pin, and the centerline of the rear wheels. This information determines the turning and tracking radii of the truck and trailer. This scheme is used for the design of islands, medians, lane widths, and turning radii on highways.

The HCM currently divides heavy vehicles into three classes for capacity analysis purposes: bus, truck, and recreational vehicle (RV). These classes are used to identify the appropriate passenger car equivalent (PCE) for each heavy-vehicle type and to compute the amount of roadway capacity consumed by each type. The PCEs may vary by terrain and road grade.

Other classification schemes are those that do not fit into one of the above categories. These schemes can include overall length classifications and those by weight such as the one used by the California Energy Commission.

Most of these schemes were designed to serve purposes other than determining effects of trucks on traffic flow. The current HCM 2010 truck classification scheme was developed explicitly for capacity analysis, but it employs a gross simplification of the varying types of trucks and their different operating characteristics. The simplification was designed to reduce data collection needs when determining capacity.

Exhibit 18. National truck classification schemes.

Classification scheme	Basis	No. types	Purpose
NHTSA	Gross vehicle weight rating	8	Safety assessments
FHWA	Axles Trailers	13	Truck classification at weigh stations Pavement design
STAA	Length	2	Limit access to certain road types
AASHTO	Wheelbase Kingpin – rear wheel C/L	7	Geometric design
HCM	Heavy vehicle that is not a bus or a recreational vehicle	1	Capacity analysis

Exhibit 19. NHTSA vehicle classification scheme.

Vehicle Class	GVWR
Class A	Not greater than 1360 kg. (3,000 lbs.)
Class B	Greater than 1360 kg. to 1814 kg. (3,001–4,000 lbs.)
Class C	Greater than 1814 kg. to 2268 kg. (4,001–5,000 lbs.)
Class D	Greater than 2268 kg. to 2722 kg. (5,001–6,000 lbs.)
Class E	Greater than 2722 kg. to 3175 kg. (6,001–7,000 lbs.)
Class F	Greater than 3175 kg. to 3629 kg. (7,001–8,000 lbs.)
Class G	Greater than 3629 kg. to 4082 kg. (8,001–9,000 lbs.)
Class H	Greater than 4082 kg. to 4536 kg. (9,001–10,000 lbs.)
Class 3	Greater than 4536 kg. to 6350 kg. (10,001–14,000 lbs.)
Class 4	Greater than 6350 kg. to 7257 kg. (14,001–16,000 lbs.)
Class 5	Greater than 7257 kg. to 8845 kg. (16,001–19,500 lbs.)
Class 6	Greater than 8845 kg. to 11793 kg. (19,501–26,000 lbs.)
Class 7	Greater than 11793 kg. to 14968 kg. (26,001–33,000 lbs.)
Class 8	Greater than 14968 kg. (33,001 lbs. and heavier)

Source: Title 49 CFR, Chapter V, Section 565.6, Table II.

5.1.1 NHTSA Classification Scheme

Vehicle manufacturers are required by federal regulations (Title 49 Code of Federal Regulations, Chapter V, Section 565.6) to submit information on the gross vehicle weight rating (GVWR) of the vehicle to NHTSA (see Exhibit 19). This rating may also be included with the vehicle's vehicle identification number (VIN). The GVWR is defined as the unloaded vehicle weight plus its maximum safe load.

5.1.2 FHWA Vehicle Classification Scheme

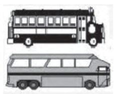
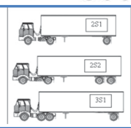
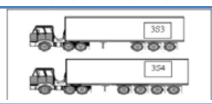
The FHWA vehicle classification scheme groups vehicles into 13 categories based on the total number of axles and the number of trailers (see Exhibit 20). A survey of state DOTs by Benekohal and Girianna (2003) reported that state DOTs generally follow the FHWA classification scheme, with some variations:

- Colorado DOT condenses the FHWA classification scheme into three categories. FHWA Classes 1–3 are grouped as passenger vehicles, Classes 4–7 are grouped as single-unit trucks, and FHWA Classes 8–13 are grouped as combination trucks.
- Illinois DOT classifies vehicles according to length of vehicles. Passenger vehicles are up to 21 ft. long, single units are between 22 and 44 ft., and multi-units are vehicles longer than 40 ft.
- Caltrans uses FHWA classification with little modification. Caltrans added two vehicles classifications in the FHWA vehicle classification system for a total of 15. FHWA Class 9 was split into two classes, single and multi-trailer. An "unclassifiable" class was added to account for an unrecognizable vehicle or equipment malfunction.
- Texas DOT modifies the FHWA scheme based on the estimated range of loaded weights and horsepower for each truck classification category. An example of this is shown in Exhibit 21.

5.1.3 STAA Classification

The Surface Transportation Assistance Act (STAA) of 1982 regulated the length of commercial motor vehicles. Congress established minimum length standards for most commercial

Exhibit 20. FHWA vehicle classification scheme.

Class	Illustration	Description
1		***Motorcycles:*** All two or three-wheeled motorized vehicles.
2		***Passenger Cars:*** All sedans, coupes, and station wagons manufactured primarily for the purpose of carrying passengers and including those passenger cars pulling recreational or other light trailers.
3		***Other Two-Axle, Four-Tire Single Unit Vehicles:*** All two-axle, four-tire vehicles other than passenger cars. Generally pick-up trucks, sports utility vehicles, vans.
4		***Buses:*** All vehicles manufactured as traditional passenger-carrying buses with two axles and six tires or three or more axles. Excludes modified buses no longer capable of mass passenger transport.
5		***Two-Axle, Six-Tire, Single-Unit Trucks:*** All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., with two axles and dual rear wheels.
6		***Three-Axle Single-Unit Trucks:*** All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., with three axles.
7		***Four or More Axle Single-Unit Trucks:*** All trucks on a single frame with four or more axles.
8		***Four or Fewer Axle Single-Trailer Trucks:*** All vehicles with four or fewer axles consisting of two units, one of which is a tractor or straight truck power unit.
9		***Five-Axle Single-Trailer* Trucks:** All five-axle vehicles consisting of two units, one of which is a tractor or straight truck power unit.
10		***Six or More Axle Single-Trailer Trucks:*** All vehicles with six or more axles consisting of two units, one of which is a tractor or straight truck power unit.
11		***Five or Fewer Axle Multi-Trailer Trucks:*** All vehicles with five or fewer axles consisting of three or more units, one of which is a tractor or straight truck power unit.
12		***Six-Axle Multi-Trailer Trucks:*** All six-axle vehicles consisting of three or more units, one of which is a tractor or straight truck power unit.
13		***Seven or More Axle Multi-Trailer Trucks:*** All vehicles with seven or more axles consisting of three or more units, one of which is a tractor or straight truck power unit.

Adapted from FHWA, 2001 and Maryland SHA, 2012.

truck tractor-semitrailers and for twin trailers pulled behind a truck tractor. The STAA act of 1982 changed the allowable width of commercial vehicles to 102 in. Previously, the Federal-Aid Highway Act of 1956 provided a maximum vehicle width of 96 in. (FHWA, 2004).

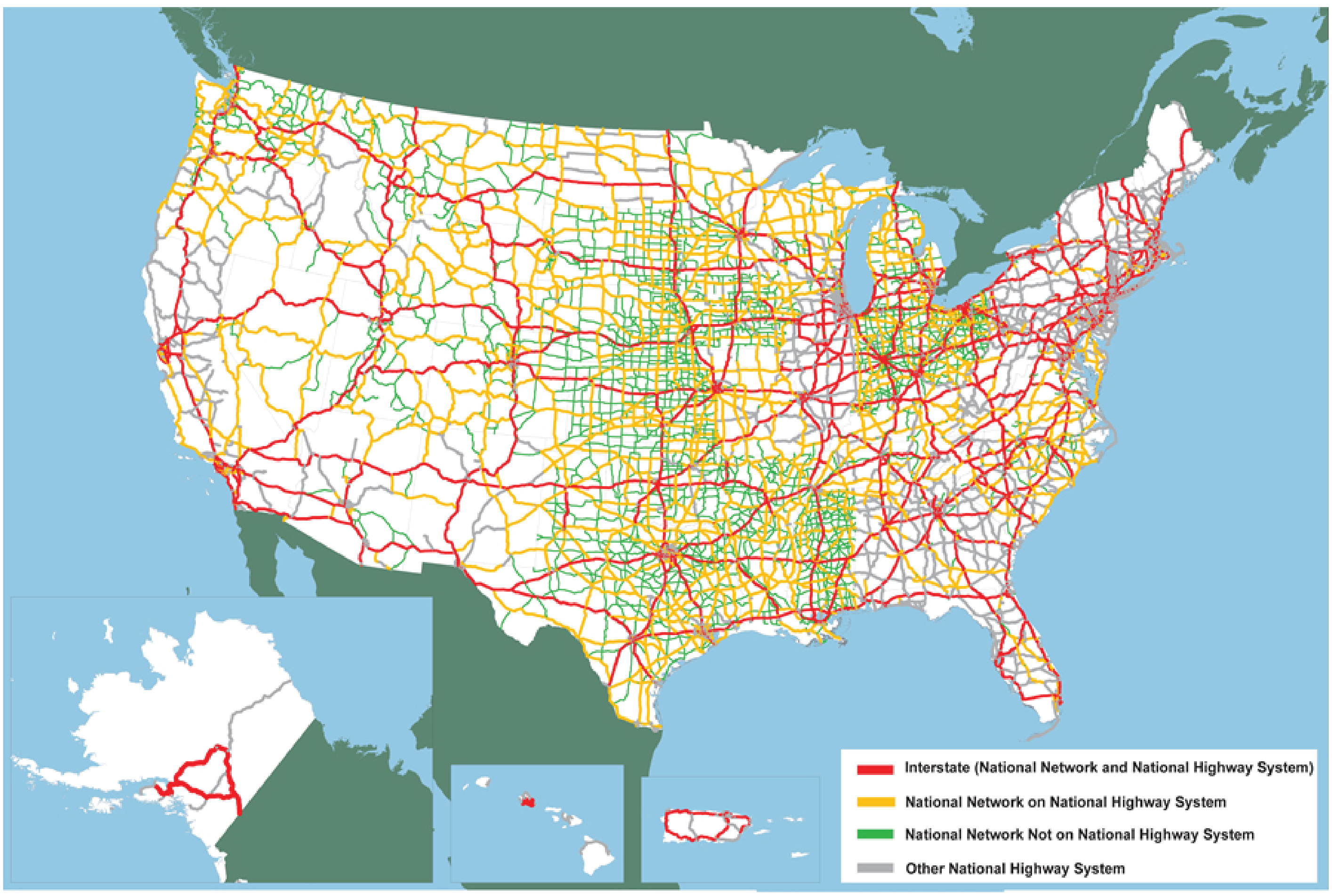
Additionally, the STAA authorized the establishment of a “National Network,” which is a network of federal highways that includes primary Interstates where federal width and length limits for heavy vehicles would apply. The National Network contains over 200,000 miles of highways across the nation (see Exhibit 22). These STAA federal length limits are minimums that states must allow for vehicles on the National Network and for the reasonable access routes to the network (FHWA, 2004).

Exhibit 21. Texas truck classification scheme.

Class		Weight (pounds)		Power (hp)
Texas	FHWA	Minimum	Maximum	
5	6	15,000	46,000	220
6	7	20,000	53,000	250
7	8	25,000	52,000	250
8	8	28,000	66,000	310
9	9	30,000	80,000	380
10	10	32,000	87,000	410
11	11	35,000	92,000	440
12	12	35,000	106,000	500
13	13	35,000	120,000	570

Note: In this exhibit, trucks are defined as vehicles with three or more axles (Middleton, 2006).

Exhibit 22. National Network and National Highway System (FHWA, 2009).



Notes: This map should not be interpreted as the official National Network and should not be used for truck size and weight enforcement purposes. The National Network and the National Highway System (NHS) are approximately 200,000 miles in length, but the National Network includes 65,000 miles of highways beyond the NHS, and the NHS encompasses about 50,000 miles of highways that are not part of the National Network. "Other NHS" refers to NHS mileage that is not included on the National Network. Conventional combination trucks are tractors with one semitrailer up to 48 feet in length or with one 28-foot semitrailer and one 28-foot trailer. Conventional combination trucks can be up to102 inches wide.
Source: U.S. Department of Transportation, Federal Highway Administration, Office of Freight Management and Operations, Freight Analysis Framework, version 2.2, 2009.

Truck Tractor-Semitrailer (Single-Trailer) Combinations

The minimum length set for the semitrailer in a single-trailer combination is 48 ft., which can be higher depending on the grandfathered limit for a particular state. In a state, semitrailers up to the maximum length that were lawfully operating in a truck tractor-semitrailer combination on December 1, 1982, may continue to operate after this date. The grandfathered semitrailer lengths vary with states—for example, Florida, Minnesota, and Idaho used 48 ft.; Oregon and Pennsylvania used 53 ft.; Texas used 59 ft.; and Louisiana used as high as 59.5 ft. States may not impose an overall vehicle length on a truck tractor-semitrailer combination operating on the National Network even if the length of vehicle exceeds the limit imposed by federal law (FHWA, 2004).

Truck Tractor-Semitrailer-Trailer (Double-Trailer) Combinations

The minimum length set for trailer and semitrailer combinations on the National Network is 28 ft. States must allow use of semitrailers of 28.5 ft. in length that were in use on December 1, 1982, provided that the overall length of the combination does not exceed 65 ft. The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) determined the maximum overall length of cargo-carrying units that states may allow for twin-trailer combinations when one trailing unit is longer than 28.5 ft. (FHWA, 2004).

Trucks or Straight Trucks

Trucks or straight trucks are non-articulated self-propelled cargo-carrying commercial motor vehicles. These types of trucks are subject to federal weight requirements on the Interstate system and federal width requirements on the National Network. They are not subject to federal length requirements, but would be subject to state length requirements.

The maximum width limit for commercial motor vehicles on the National Network and reasonable access route was established to be 102 in. except in Hawaii (where it is 108 in.). The federal width limits do not apply for special mobile equipment such as the following: military or farm equipment, instruments of husbandry, road construction or maintenance machinery, and emergency apparatus including police and fire emergency equipment (FHWA, 2004).

There are also specific federal length limits and provisions for six types of specialized equipment: automobile and boat transporter combinations, B-train combinations, beverage semitrailers, maxi-cube vehicles, saddle mount combinations, and dromedaries.

5.1.4 AASHTO Truck Classification Scheme

AASHTO classified four types of design vehicles: passenger cars, buses, trucks, and RVs. Under the truck category, the seven types of truck design vehicles are listed in Exhibit 23. The purpose of

Exhibit 23. AASHTO truck classification (design vehicles) (AASHTO, 2011).

Design Vehicle	Symbol	Overall Length (ft.)
Intermediate Semitrailer	WB-40	45.5
Intermediate Semitrailer	WB-50	55.0
Interstate Semitrailer	WB-62	68.5
Interstate Semitrailer	WB-65 or WB-67	73.5
Double Bottom–Semitrailer/ Trailer	WB-67D	73.3
Triple Semitrailer/ Trailer	WB-100T	104.8
Turnpike Double–Semitrailer/ Trailer	WB-109D	114.0

Exhibit 24. Length-based classification boundaries (FHWA, 2001).

Primary Description	Minimum Length (>) (ft.)	Maximum Length (≤) (ft.)
Passenger Vehicles	0	13
Single-Unit Trucks	13	35
Combination of Trucks	35	61
Multi-trailer Trucks	61	120

the AASHTO design vehicles is to ensure adequate lane widths, turning radii, and other geometric features for trucks in the design of streets and highways.

5.2 Other Classification Schemes

Besides axles, the number of trailers, weight, and trailer length, there are other classification schemes based on overall length (facilitates automated counts), emissions (for air-quality analysis), and fuel consumption.

5.2.1 Length-Based Classification

It is not always possible to place axle sensors to collect the 13 FHWA vehicle categories; however, it is possible to use two inductance loops or magnetic units to differentiate vehicles by total length in most cases. FHWA recommends four vehicle classes when collecting data in this fashion (FHWA, 2001). These four classes are cars (and pick-up trucks), single-unit trucks, single-trailer combination trucks, and multi-trailer trucks. The latter three vehicle types are classified as trucks based on vehicle length. In some states, the multi-trailer truck category may be unnecessary because of fewer vehicles in this category and because this category can be combined with single-trailer combination trucks.

Vehicle lengths tend to vary from state to state, but the vehicle length classification that best appears to cover combined data from all states is shown in Exhibit 24. Many states can improve these results by using different length spacing boundaries to account for characteristics of their own truck fleets. However, it should be noted that total vehicle length is not a consistent indicator of vehicle class.

5.2.2 Energy- and Emissions-Based Truck Classifications

The California Energy Commission and the California Air Resources Board have defined truck classification schemes for the respective purposes of estimating fuel use and emissions. These classification schemes are shown in Exhibit 25.

Exhibit 25. Example fuel- and emissions-based classifications.

California Energy Commission		California Air Resources Board	
Class	**Weight (lbs)**	**Class**	**Weight (lbs)**
1	0 – 6,000	T1 LDT 1	0 – 3,750
		T2 LDT 2	3,751 – 5,750
2A	6,001 – 8,500	T3 MDT	5,751 – 8,500
2B	8,501 – 10,000	T4 LHDT1	8,501 – 10,000
3	10,001 – 14,000	T5 LHDT2	10,001 – 14,000
4	14,001 – 16,000	T6 MHDT	14,001 – 33,000
5	16,001 – 19,500		
6	19,500 – 26,000		
7	26,000 – 33,000		
8	33,001 +	T7 HHDT	33,001 +

Source: Dowling Associates, 2012.

5.3 HCM Vehicle Classification

HCM classifications were developed to assess the effects of trucks on highway capacity. The HCM defines three non-automobile vehicle types: transit buses, RVs, and trucks. These three types are grouped in the HCM under the broader category of heavy vehicles (TRB, 2010).

A heavy vehicle is defined in the HCM as "A vehicle with more than four wheels touching the pavement during normal operation." Buses, RVs, and trucks are then heavy vehicles with the following special characteristics:

- A **bus** is defined as "A self-propelled, rubber-tired road vehicle designed to carry a substantial number of passengers (at least 16) and commonly operated on streets and highways" (equivalent to FHWA Class 4).
- An **RV** is defined as "A heavy vehicle, generally operated by a private motorist, for transporting recreational equipment or facilities; examples include campers, motor homes, and vehicles towing boat trailers" (generally equivalent to FHWA Class 5).
- A **truck** is defined as "A heavy vehicle engaged primarily in the transport of goods and materials or used in the delivery of services other than public transportation" (equivalent to FHWA Classes 5–13).

Each heavy-vehicle type can be assigned its own PCE value for the purposes of capacity and operational analyses. However, the HCM groups them together for most analyses. Some examples of how the HCM groups heavy vehicles for different facilities include

- **Freeways and multilane highways**—the HCM groups buses and trucks together, assigning them the same PCE values. RVs are given a slightly lower PCE value.
- **Two-lane highways**—the HCM does not provide a PCE for buses. Trucks are assigned a PCE, and RVs are given a slightly lower PCE value.
- **Urban streets**—a single PCE value of 2.0 is used for the entire group of heavy vehicles.

HCM 2010 has adopted a capacity estimation method using PCEs that were calibrated for a mix of trucks and buses in an average weight-to-horsepower ratio of between 125 and 150 lb/hp. (HCM 2010: Chapter 11). However, Middleton (2006) found a variety of trucks with higher weight-to-power ratios. Middleton's research indicated that the weight-to-horsepower values could reach 210 lb/hp. This is the basis of the tabulated maximum weights by FHWA weight class shown in Exhibit 26.

As can be seen in Exhibit 26, the HCM heavy-vehicle classifications are much broader than other national classification schemes. They do not take into account that truck performance characteristics are determined to a large degree by weight-to-power ratio. Historically, this

Exhibit 26. Physical and performance characteristics of trucks.*

Class	Weight (pounds)		Power (hp)	**Range of Weight/Horsepower
FHWA	Minimum	Maximum		
6	15,000	46,000	220	68 – 209
7	20,000	53,000	250	80 – 212
8	28,000	66,000	310	90 – 213
9	30,000	80,000	380	79 – 211
10	30,000	87,000	410	73 – 212
11	35,000	92,000	440	80 – 209
12	35,000	106,000	500	70 – 212
13	35,000	120,000	570	61 – 211

*Researchers defined trucks as vehicles with three or more axles (Middleton, 2006).
**Estimated from weight and power values.

simplistic approach was taken by the HCM to reduce data collection requirements for capacity analysis. However, with the new automated data collection sources available (specifically Weigh-in-Motion), it may now be possible to use more disaggregate classifications of heavy vehicles in an HCM analysis to yield more accurate performance and capacity estimates.

5.4 Determinants of Truck Performance in a Traffic Stream

The following are the main factors that determine effects of truck performance on traffic flow:

- Engine power (net power delivered to the drive axle),
- Gross vehicle weight,
- Losses due to rolling resistance and aerodynamic drag,
- Terrain type (percent grade and length of grade), and
- Vehicle length.

The first four of these determine the maximum acceleration rate for a truck and how much a truck will slow down on a grade. The fifth is the physical space taken up by a truck. Although it is often assumed that vehicle length represents the amount of capacity taken up by a truck, investigations have shown that effects of trucks on traffic flow are far more complex. Traffic flow shows dependence on the mix of trucks, overall truck percentage, and grade (Rakha et al., 2007). Investigation of truck acceleration characteristics shows a critical dependence of maximum acceleration rates to power-to-weight ratios (Rakha et al., 2001; Middleton, 2006).

On level terrain, it can be shown that the maximum acceleration of a vehicle is given by

$$a_{\max} = 8226/(WEHPR * V) \qquad \text{Equation 6}$$

where

$a_{\max}$ = maximum acceleration (mph/s),
$WEHPR$ = weight-to-effective horsepower ratio (lb/hp), and
V = vehicle speed (mph).

The effective horsepower is what is available for acceleration after the effects of transmission loss, aerodynamic drag, and rolling resistance are accounted for. Therefore, for a truck with a WEHPR of 300 traveling at 55 mph, the maximum acceleration would be about 0.5 mph/s. Middleton (2006) showed how truck acceleration characteristics were determined for various vehicle classes, which were used to calibrate a traffic microsimulation model.

Weight-to-horsepower ratio is also a determinant of the maximum sustainable speed of a vehicle on a grade. The maximum sustainable speed of a truck on a grade is given by

$$V_{\max} = 375/(WEHPR * g) \qquad \text{Equation 7}$$

where

$V_{\max}$ = the maximum sustainable speed,
g = grade (expressed as a fraction), and
$WEHPR$ = weight-to-effective horsepower ratio (lb/hp).

For example, a truck with an effective WEHPR of 300 on a grade of 6% can sustain a maximum speed of only about 20 mph. Trucks entering a steep grade typically have their speeds "decay" to this maximum sustainable speed within about one-quarter to one-half mile.

Weight-to-horsepower also determines how quickly a vehicle can accelerate from a standing start. This is an important factor when trucks operate on signalized roadways (arterials). The minimum time for a vehicle at a standstill with a fixed WEHPR to accelerate to a speed V on a level surface is given by

$$t_{\min} = 6.1 * 10^{-5} * WEHPR * V^2 \qquad \text{Equation 8}$$

where

V = speed (mph),
$t_{\min}$ = minimum time (s), and
$WEHPR$ = weight-to-effective horsepower ratio (lb/hp).

A truck with a WEHPR of 300 would take a minimum of 16 seconds to reach a speed of 30 mph, for example. Given the dependence of truck performance on weight-to-horsepower ratio, it can be seen from the weight and horsepower ranges shown in Exhibit 26 that the FHWA truck classification scheme covers a very large range of actual truck performance capabilities.

For urban streets and intersections, there are issues with low saturation flow rates for trucks at signals; low progression speeds on arterials; and gap acceptance at unsignalized intersections and roundabouts.

5.5 Data Collection Considerations

A classification scheme that requires significant effort to collect the data needed for analysis will reduce the likelihood of agencies using any classification scheme developed. Recent advances in automated data collection technologies are making it easier to collect large amounts of truck data with less effort on the part of transportation agencies. These automated systems are able to collect various truck characteristics that have expanded the possibilities for employing more elaborate truck classification schemes than are currently used in the HCM.

There are different automated data collection technologies and each technology has its strengths and weaknesses. The cost, reliability, precision, life span, installation, maintenance, and type of data provided also vary with the technology (Benekohal and Girianna, 2003).

Vehicle classification technologies can be grouped into the following three categories: axle-based, vehicle-length-based, and machine-vision-based. Benekohal and Girianna suggested that the accuracy of the classifiers depends on several factors including the type of sensor used (loop, tube, piezoelectric, etc.); roadway geometry conditions at the site of classification; installation and maintenance; and classification algorithms. Some errors are due to incorrect measurement of the number of axles, a considerable change in vehicle speed over the sensors, or vehicles that do not fit into any of the defined classes of vehicles.

5.5.1 Video Camera Data Collection

Video cameras with the appropriate software can classify vehicles based on overall length. A single sensor or combinations of different types of sensors are used. Based on this detection method, there may be fewer categories than FHWA's 13 vehicle classes because of the difficulty of differentiating a single long vehicle unit from two smaller or shorter units hitched together. The vehicle length classifiers remain popular in some states because fewer categories are sufficient for a variety of traffic monitoring purposes (Benekohal and Girianna, 2003).

The machine vision–based classifiers combine video imaging with computerized pattern recognition. A video camera is used to record video images that are taken continuously at regular time intervals. A digitizer converts the frames into digital signals that are sent to a computer for extraction of vehicle features. Some of the limitations of the machine vision–based classifier are measuring speed accurately and difficulties in differentiating among closely spaced vehicles. Research and development are underway on new sensor technologies to obtain more accurate vehicle classifications.

5.5.2 Weigh-In-Motion Data Collection

WIM devices measure axle weights and gross vehicle weights as vehicles drive over the detection site. They are more efficient than traditional weigh stations because they can measure weights at normal operating speeds. WIM data provides information on the distribution of actual truck weights as they are measured at the time. It can provide a finer stratification of trucks by weight than can be provided using just the FHWA vehicle classification scheme. Data are also provided on truck speeds, although these are usually "binned" into 5 mph groups.

5.5.3 Highway Performance Monitoring Systems Truck Classification Data

HPMS provide data on pavement conditions, geometry, terrain, weather, and traffic counts on a selected sample of roads across various functional classes. A subset of the sample data contains information on percentage truck traffic by two classes: single-unit trucks and combination-unit trucks. This data may be estimated or it may be counted. HPMS data are in some sense broader in coverage than most other traffic classification data sources. HPMS truck categories are often too broad to be of much use for operational analysis. Counts are presented as average daily values and average percent trucks, which are not useful for analyses of peak periods of congestion. Agencies must have the labor and analytical capacity required to process the HPMS data collected.

5.6 Trucking/Shipping Industry Perspectives

From the point of view of shippers and carriers, the value of time for a given truck depends more on the type of load carried than on the weight of the load. A truck hauling gravel will have a different value of time (and value of reliability) than a concrete truck hauling wet concrete or high value, just-in-time delivery, electronic goods. The available data and the available classification schemes do not provide a means to sort low time value loads from high time value loads.

5.7 Recommended NCFRP Project 41 HCM Truck Classification Scheme

The truck classification scheme for purposes of this research should serve the following purposes:

- Accurately determine the effects of trucks on traffic operations according to the mix of trucks of different types in the traffic stream and
- Provide managers and decisionmakers with sufficient information to estimate the cost-effectiveness of different types and scales of operational improvements and capacity enhancements.

It is clear that the available truck classification schemes do not directly serve these purposes. They are either directed at truck characteristics that bear only indirectly on these purposes, or they are so broad that they mask truck performance differences that affect traffic flow and, therefore, lose accuracy in the process.

The ideal truck classification scheme would take into account

- Truck length and weight-to-horsepower ratio (so as to estimate the capacity and speed effects of trucks on automobile traffic) and
- Whether the truck is loaded or unloaded and the value of the goods carried (so as to estimate the importance of reliability and average travel time to trucks).

At this point in time, it is not practical to gather data on these characteristics of trucks using any given facility.

The FHWA vehicle classification scheme—although it lacks the ability to take into account weight-to-horsepower ratio—has the advantage of being a nationally established classification scheme for which technologies have been developed for the automatic collection of data by vehicle class.

The FHWA vehicle classification scheme is based primarily on the number of axles, which is a rough proxy for vehicle length. WIM stations are capable of assigning measured weights by vehicle class at the station.

Given the lack of information on specific weight-to-horsepower ratios by vehicle class, it is recommended that the number of FHWA vehicle classes be condensed from 13 to 5 for highway capacity analysis purposes:

1. Motorcycles (FHWA Class 1);
2. Passenger vehicles (FHWA Classes 2, 3);
3. Buses (FHWA Class 4);
4. Single-unit trucks (FHWA Classes 5–7); and
5. Semi-trailer combination trucks (FHWA Classes 8–13).

The recommendation to split trucks into two types (single-unit and semitrailer trucks) is supported by statewide data on truck types collected by Stone et al. (2010) for more than 600 locations where vehicle classification counts were collected as well as more than 50 WIM stations. Overwhelmingly, the trucks fell into FHWA Truck Classes 5 and 9. The following table from Stone et al. (see Exhibit 27) shows the breakdown for 10 random WIM locations. Note the high percentage of Class 5 and 9 trucks. These two classes alone account for 75% of the truck traffic observed on North Carolina roads.

Exhibit 27. Percentage of trucks on road by FHWA class—North Carolina.

ID	Route	Date	VC4	VC5	VC6	VC7	VC8	VC9	VC10	VC11	VC12	VC13	Total
VC1903	US 64	02-27-06	5%	31%	8%	0%	16%	37%	3%	0%	0%	0%	100%
VC1904	NC 294	02-20-07	4%	44%	11%	0%	15%	26%	0%	0%	0%	0%	100%
VC1905	NC 60	02-20-07	4%	39%	9%	1%	6%	33%	7%	0%	0%	1%	100%
VC1902	US 19	11-13-06	5%	47%	11%	0%	7%	27%	2%	0%	0%	1%	100%
VC2104	US 64	05-01-07	3%	49%	9%	0%	9%	28%	2%	0%	0%	0%	100%
VC2102	NC 69	09-25-06	4%	23%	5%	1%	10%	56%	1%	0%	0%	0%	100%
VC2103	NC 175	02-20-07	6%	66%	11%	1%	10%	5%	0%	0%	0%	1%	100%
VC5508	US 64	05-01-07	4%	16%	5%	0%	5%	65%	1%	3%	1%	0%	100%
VC5501	US 23	10-09-06	6%	19%	2%	0%	8%	61%	1%	2%	1%	0%	100%
VC3701	US 129	08-22-06	3%	20%	5%	1%	8%	59%	3%	1%	0%	0%	100%
Average			4%	35%	8%	0%	9%	40%	2%	1%	0%	0%	100%

VC = FHWA Vehicle Class; adapted from Stone et al., 2010.

Future research may be able to develop data collection methods so that analysts conducting capacity analyses can segregate the single unit trucks and the semitrailer trucks observed on a given facility by their weight-to-horsepower ratio, thereby further refining their ability to estimate the capacity and speed effects of trucks.

Note that motorcycles, passenger vehicles, and buses are not the subject of the current research project. The HCM already includes methods for evaluating the capacity effects of passenger vehicles and buses. Also note that RVs, currently a separate non-truck vehicle type in the HCM, fall within the FHWA definition for Vehicle Class 5.

SECTION 6

Truck Level-of-Service Framework

This section describes the development of a truck LOS model framework that is sensitive to the facility performance measures that are most important from the perspective of shippers, receivers and carriers, tempered with the need to provide actionable information to public agencies for the improvement of truck movements on the facility.

The truck LOS model development process started with the Cambridge Systematics New York/New Jersey Cross Harbor Freight Movement Model (Cambridge Systematics, in process). This original model, designed to analyze the entire truck trip, was adapted to the analysis of single freeway or street facilities, with the more limited goods-movement information available at that level. The model was then streamlined with the use of several default values for critical information on goods-movement characteristics in order to facilitate its application by public agencies. Finally, an alternative form was developed for the model to make its operation and results more intuitive for use by public agencies communicating their results to decisionmakers and the general public.

The models were vetted with freight experts from various public agencies in two workshops to identify the model best suited for their use in evaluating highway freight improvement projects and for goods-movement planning.

6.1 Establishing a Facility's Freight Importance Class

It is desirable to be able to set different LOS thresholds according to the importance of the facility to the economic vitality of the region. Thus, an inter-regional freeway or highway critical for importing and exporting goods from the region is a vital link in the region's freight system. Freeways and arterial streets serving a major regional intermodal terminal such as a water port, an airport, or a railroad intermodal facility may also be vital links in the region's freight system. Roads serving a major factory complex may also be vital links for the region's freight system.

FHWA, working in conjunction with the states, has established the National Highway System (NHS) (FHWA, 2013), which consists of roadways important to the nation's economy, defense, and mobility. The NHS consists of Interstate highways, other principal arterials, the Strategic Highway Network, major strategic highway network connectors (connectors to major military installations), and intermodal connectors.

MAP-21, the Moving Ahead for Progress in the 21st Century Act (P.L. 112-141), "requires [the Department of Transportation] to establish a national freight network to assist States in strategically directing resources toward improved movement of freight on highways. The national freight network will consist of three components:

- A primary freight network (PFN),
- Any portions of the Interstate System not designated as part of the PFN, and
- Critical rural freight corridors." (Federal Register, 2013)

Exhibit 28. Facility freight classification system.

Facility Class	Description	Suggested Criteria	Examples
I	Highway facility critical to the inter-regional or within region movement of goods.	• Facility carries a high volume of goods by truck (by tonnage or by value). • Trucks may account for a high volume or percentage of AADT* compared with other facilities in the region.	Interstate freeway, inter-regional rural principal arterial.
II	Highway facility of secondary importance to goods movement within or between regions.	• Facility carries lesser volumes of goods (by tonnage or value). • Trucks account for a lesser volume or percentage of AADT.	Urban principal arterial, connector to major intermodal facilities (maritime port, intermodal rail terminal, airports).
III	Highway facility of tertiary importance to goods movement within or between regions.	• Connectors to significant single origins/destinations of goods, such as major manufacturing facilities, sources of raw materials (mines, oil, etc.). • Connectors to truck service facilities and terminals.	Access roads to mines, energy production facilities, factories, truck stops, truck terminals.

*AADT = annual average daily traffic.

Since designation of the National Freight Network is not expected until after preparation of this report, a tentative three-class system (shown in Exhibit 28) employing some of the general criteria outlined in MAP-21 is recommended for classifying highway facilities by their relative importance to the region's and national economy.

The different classes of facilities are assigned different percentage thresholds for a given letter grade LOS (see Exhibit 29). The thresholds are higher for higher-class facilities and lower for the lower-class facilities.

6.2 Derivation of LOS Model 1

The Cambridge Systematics Port Authority model (described in Section 3.5) needed to be simplified and adapted for application within the single highway facility analysis environment typical of HCM analyses. The unique goods movement inputs of the Cambridge model needed to be replaced with regional defaults to enable application of the model using the data resources typically available for an HCM analysis. The derivation of Model 1 from the Cambridge model proceeds through several steps.

Exhibit 29. LOS Model 1 service measures and thresholds for goods movement LOS.*

LOS	Class I Primary Freight Facility	Class II Secondary Facility	Class III Tertiary Facility
A	>=90%	>=85%	>=80%
B	>=80%	>=75%	>=70%
C	>=70%	>=65%	>=60%
D	>=60%	>=55%	>=50%
E	>=50%	>=45%	>=40%
F	<50%	<45%	<40%

*Entries are the percentage of achievement of ideal facility operating conditions for trucks.

6.2.1 Translation of Utility to LOS

The utility index output by the Cambridge model must be translated into an equivalent letter grade LOS. This is done by comparing the computed utility for actual conditions on the facility with the estimated utilities for the theoretically best- and worst-case conditions on the facility. The "closeness" of actual performance to ideal, best performance is used to assign the letter grade LOS. Conditions close to ideal, best case are assigned a letter grade of "A." Conditions far worse are assigned a letter grade of "F."

Both the best- and the worst-case conditions for the facility would be set based on local operating agency preferences. The best case would presumably represent free-flow conditions with highly reliable travel times with modest to no tolls on the facility, but this is up to the agency. The worst case would represent severe congestion, highly unreliable travel times, and a toll condition specified by the operating agency.

The Truck Level of Service (TLOS) Index is then computed as follows:

$$TLOS(Index) = \frac{U(actual) - U(worst)}{U(best) - U(worst)} \qquad \text{Equation 9}$$

where

$TLOS(Index)$ = ratio of actual utility to utility for ideal conditions (constant free flow speed, no tolls) and

$U(x)$ = utility of trip on facility under conditions "x."

Exhibit 29 shows the recommended thresholds by LOS grade by facility class (facility classes were described in Section 6.1).

6.2.2 Translation of Facility Changes to Shipment Changes

The Cambridge model is designed to be applied to the entire truck trip, while HCM analyses apply to individual facilities. In order to use the Cambridge model in an HCM analysis, it is necessary to translate facility performance changes into their equivalent effects on the entire truck trip.

Translating Facility Travel Time Effects into Shipment Travel Time Changes

The average shipment travel time by commodity type is obtained from the table of suggested defaults provided in Exhibit 30. The average shipment time for each commodity type was estimated by applying assumed typical freeway and arterial free-flow speeds to the average shipment distances obtained from FHWA's Freight Analysis Framework (FAF).

The effect of actual facility travel times for the selected analysis period on the average shipment times by commodity type are estimated by adding the difference between the actual facility travel time and the free-flow travel time for the facility:

$$AST(c,(s=a),r) = AST(c,(s=b),r) + T(s=a) - T(s=b) \qquad \text{Equation 10}$$

where

$AST(c,s,r)$ = Average shipment time for commodity "c," scenario "s," and region "r," where commodity types and regions are as shown in Exhibit 30 and scenarios are best case ($s = b$), actual case ($s = a$), or worst case ($s = w$) and

$T(s)$ = End-to-end facility travel time under scenario "s."

Exhibit 30. Default average shipment times by commodity type by region.*

Average Shipment Time by Commodity Type (hr)	Pacific	Rocky Mountains	Southwest	Midwest	Northeast	Southeast	Alaska	Hawaii
Agriculture	5.1	4.4	4.1	2.9	4.0	3.8	4.7	0.6
Metal and Mining	2.9	2.9	3.2	2.9	2.6	2.8	5.4	0.6
Construction	1.4	1.7	1.4	1.5	1.1	1.4	3.9	0.6
Chemical	3.5	4.2	3.3	3.0	2.5	3.0	4.9	0.6
Wood and Paper	4.5	4.8	4.7	4.5	3.7	3.0	6.0	0.6
Electronics	11.5	9.1	10.6	8.6	8.8	8.3	21.7	0.5
Transportation and Utility	9.1	9.0	7.2	5.8	6.3	5.8	17.9	0.6
Wholesale and Retail	5.3	5.1	4.4	3.9	3.5	4.1	13.1	0.6
Regional Average	3.7	3.6	3.3	2.9	2.8	2.8	5.2	0.6

*Data extracted from FHWA Freight Analysis Framework; values computed by Kittelson and Associates. See Appendix A for derivation of average shipment times.

The same approach is used to estimate the effect of worse-case conditions on average shipment times. The difference between the agency selected worst-case congested travel time and the free-flow travel time for the facility is added to the average shipment time obtained from FHWA's FAF.

Translating Facility Reliability into Probability of On-Time Arrival

The Cambridge model uses the probability of on-time arrival to estimate utility; however, for typical HCM analyses, only facility reliability will be available. Facility reliability may be expressed in many forms such as the 85th-percentile travel time index (TTI) or the probability of automobile LOS F operation.

The definition of on-time arrival is obviously specific for each shipment. For the purposes of highway planning, an agency may select an average value of on-time arrival that reflects agency goals such as the difference between free-flow speeds and congested speeds on the facility. Following such a policy, an agency might define on-time arrival for a freeway as average truck travel times on the facility that are no more than 33% greater than free-flow travel times. Following this policy the 85th-percentile and 90th-percentile TTIs for the facility can be translated into probability of on-time arrival as follows:

$$\text{if TTI}(85\text{th}\%) > 1.33, \textit{ then probability of on-time arrival} < 85\%,$$

$$\text{if TTI}(90\text{th}\%) < 1.33, \textit{ then probability of on-time arrival} > 90\%,$$

$$\text{Else probability of on-time arrival is between 85\% and 90\%} \qquad \text{Equation 11}$$

where

$TTI\ (P)$ = ratio of the "P" percentile highest travel time on facility to the free-flow travel time.

Following the recommended reliability LOS thresholds suggested by SHRP2-L08 (Kittelson and Vandehey, 2012) the threshold for on-time arrival is set at the conventional HCM LOS E/F threshold for the facility. If the facility is operating at LOS F then the truck is assumed to not arrive on time. For freeways, LOS F will usually occur when TTI exceeds 1.33. For arterials, LOS F will usually occur when the TTI exceeds 3.33 (the midblock free-flow speed divided by the LOS F travel speed).

Exhibit 31. Average shipment costs by commodity type and region.*

Average Shipment Cost ($)	Pacific	Rocky Mountains	Southwest	Midwest	Northeast	Southeast	Alaska	Hawaii
Agriculture	$1,200	$1,000	$1,000	$700	$900	$900	$1,200	$100
Metal and Mining	$700	$700	$800	$700	$600	$700	$1,300	$100
Construction	$300	$400	$300	$300	$300	$300	$1,000	$100
Chemical	$800	$1,000	$800	$700	$600	$700	$1,200	$100
Wood and Paper	$1,000	$1,100	$1,100	$1,000	$900	$700	$1,500	$100
Electronics	$2,700	$2,100	$2,500	$2,000	$2,100	$2,000	$5,400	$100
Transportation and Utility	$2,100	$2,100	$1,700	$1,400	$1,500	$1,400	$4,400	$100
Wholesale and Retail	$1,200	$1,200	$1,000	$900	$800	$1,000	$3,200	$100
Regional Average	$800	$800	$800	$700	$700	$700	$1,300	$100

*Data extracted from FHWA Freight Analysis Framework; values computed by Kittelson and Associates. See Appendix A for derivation of average shipment times.

Estimation of Effect of Tolls on Average Shipment Cost

The Cambridge model requires average shipment cost by commodity type. Changes in facility tolls would change that cost upwards or downwards. A table of default average shipment costs (shown in Exhibit 31) has been derived from FHWA FAF data.

Any changes in facility tolls applicable to trucks are added to the average shipment costs for the commodities:

$$ASC(c, s=a, r) = ASC(c, s=b, r) + Tolls(s=a) - Tolls(s=b) \quad \text{Equation 12}$$

where

$ASC(c,s,r)$ = Average shipment cost for commodity "c," scenario "s," and region "r," where commodity types and regions are as shown in Exhibit 30 and scenarios are best case ($s = b$), actual case ($s = a$), or worst case ($s = w$) (in dollars) and

$Toll(s)$ = End-to-end facility toll for trucks under scenario "s" (in dollars).

The average shipment costs are related to the average shipment distances given in Exhibit 32.

Exhibit 32. Average truck shipment distance.*

Average Shipment Distance (miles)	Pacific	Rocky Mountains	Southwest	Midwest	Northeast	Southeast	Alaska	Hawaii
Agriculture	330	280	260	180	260	240	250	20
Metal and Mining	180	180	210	180	160	180	290	20
Construction	90	110	90	90	70	90	210	30
Chemical	220	270	210	190	160	190	260	30
Wood and Paper	280	300	300	280	230	190	320	20
Electronics	730	570	680	550	560	530	1170	20
Transportation and Utility	580	570	450	370	400	370	970	20
Wholesale and Retail	330	320	280	240	220	260	710	20
Regional Average	230	230	210	180	180	180	280	30

*Data extracted from FHWA Freight Analysis Framework; values computed by Kittelson and Associates. See Appendix A for derivation of average shipment times.

Exhibit 33. Default table of percent of truck movements by commodity type by region.*

Percent Ton-Miles by Commodity Type	Pacific	Rocky Mountains	South-West	Midwest	North-East	South-East	Alaska	Hawaii
Agriculture	19%	26%	16%	33%	15%	14%	13%	8%
Metal and Mining	35%	35%	36%	30%	36%	32%	31%	44%
Construction	16%	13%	19%	15%	16%	21%	26%	31%
Chemical	10%	10%	16%	9%	15%	11%	19%	7%
Wood and Paper	10%	7%	5%	5%	8%	14%	6%	4%
Electronics	1%	1%	1%	1%	1%	1%	0%	0%
Transportation and Utility	2%	1%	1%	2%	1%	1%	1%	1%
Wholesale and Retail	7%	6%	6%	5%	8%	6%	4%	5%
Total	100%	100%	100%	100%	100%	100%	100%	100%

*Data extracted from FHWA Freight Analysis Framework; values computed by Kittelson and Associates. See Appendix A for derivation of average shipment times.

Computation of Composite Utility

The Cambridge model computes utility for individual commodity types. A composite utility is computed for trucks on the facility by weighting the utility for each specific commodity type by its proportion of total truck commodity flows (in tons) in the region. Default proportions by commodity type (see Exhibit 33) were obtained from the FHWA FAF for the major regions of the United States.

6.3 Derivation of Model 2

Based on concerns regarding the sensitivities, computational complexities, and data requirements of Model 1, various steps were taken to streamline the model and improve its usefulness for highway planning.

6.3.1 Graduated Effects of Reliability

It was noted in the tests of Model 1 that reliability (specifically on-time arrival) was insensitive to changes in reliability when the probabilities of on-time arrival dropped below 85% or exceeded 90%. The model consequently showed no incremental benefits of reliability improvements until the 85% tipping point was reached.

To provide for LOS sensitivity over the full range of possible probabilities of on-time arrival, a straight line function was created to approximate and replace the three-value on-time arrival variable in the original utility model. An equation with a slope of +5 and an intercept of –5 provided a reasonable fit to the original three-value OTA variable at the 85% probability of OTA without going into the positive range for probabilities of on-time arrival exceeding 95% (see Exhibit 34). The equation for estimating the contribution of reliability to utility is as follows:

$$OTA = 5.0 * POTA - 5.0 \qquad \text{Equation 13}$$

Exhibit 34. Comparison of original OTA values and straight line approximation.

Probability of On-Time Arrival	Original OTA value	Straight Line Approximation
0% to 85%	–0.758	–5.000 to –0.750
85% to 90%	–0.275	–0.750 to –0.500
90% to 100%	0.000	–0.500 to 0.000

where

OTA = on-time arrival contribution to utility equation (utils) and
$POTA$ = probability of on-time arrival expressed as a proportion (unitless).

6.3.2 Estimation of OTA Probabilities from Travel Time Indices

If the cumulative distribution of TTIs for the facility is available, it is a simple matter for the analyst to read the probability of on-time arrival for any selected on-time arrival threshold—for example, the threshold might be defined as 1.33 times the free-flow travel time (see Exhibit 35).

If only the median (50%) and 95th-percentile TTIs are available to the analyst, then the probability of on-time arrival for a selected target TTI (e.g., 1.10) can be estimated using a fitted Burr Distribution (Burr, 1942):

$$P(TTI) = 1 - (1 + TTI^{c})^{-k} \qquad \text{Equation 14}$$

where

$P(TTI)$ = cumulative probability of TTI;
TTI = desired target travel time index; and
$c, -k$ = distribution parameters, both greater than zero.

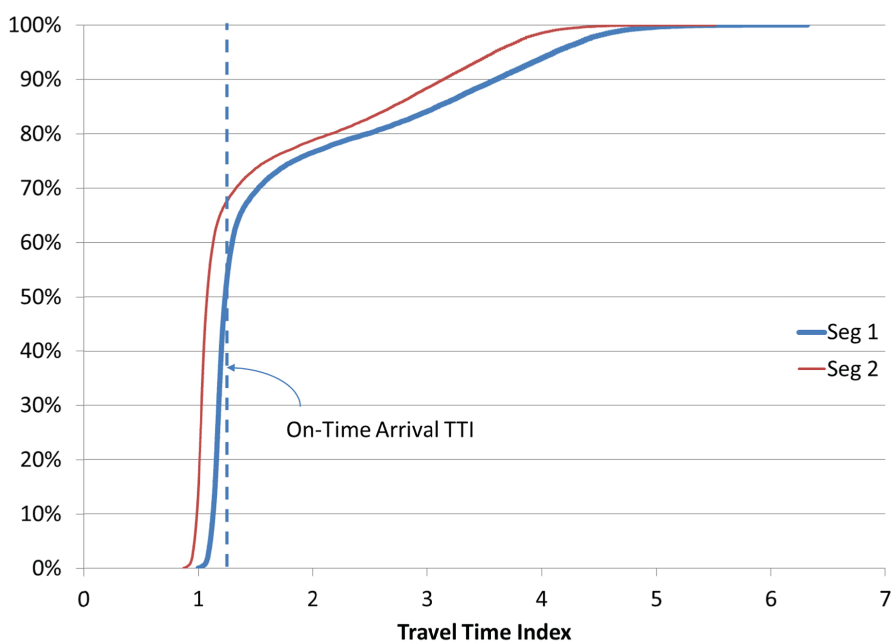
Solving for the value of TTI that represents a certain cumulative percentile of the distribution (Taylor and Susilawati, 2012):

$$TTI(P) = \sqrt[c]{(1-P)^{-1/k} - 1} \qquad \text{Equation 15}$$

where

$TTI(P)$ = percentile (P) of TTI.

Exhibit 35. Probability of on-time arrival from cumulative distribution of TTIs.



Thus, the median (50th-) and 95th-percentile TTIs are

$$TTI(50\%) = \sqrt[c]{(2)^{-1/k} - 1} \quad \text{Equation 16}$$

$$TTI(95\%) = \sqrt[c]{(20)^{-1/k} - 1} \quad \text{Equation 17}$$

Equations 16 and 17 are solved for the two unknowns: k and c. One then uses these values of k and c plus the agency's target on-time arrival threshold TTI to estimate the probability of on-time arrival.

6.3.3 Replacement of Commodity Types with Single Generic Type

To increase the appeal of the procedure to transportation engineers and planners not familiar with goods movement and the collection of goods movement flows by commodity type, the potential of condensing the original nine commodity types in the Cambridge model into a single generic commodity type was evaluated. Examination of the sensitivity of the utilities for the nine different commodity types to time and cost noted the following:

- All commodities are identically sensitive to reliability in the Cambridge model.
- All commodities are identically sensitive to travel time for shipment times less than 10 hrs.
- The sensitivities of the commodities to shipping cost vary significantly across types, but appear to fall into two main categories: highly price-sensitive goods (with cost coefficients ranging between –0.0086 and –0.0109) and less price-sensitive goods (with cost coefficients ranging between –0.0060 and –0.0068).

Based on this examination, it was concluded that the nine original commodity types could be grouped into two classes: one class less sensitive to travel time and cost (transportation, utility, wholesale and retail goods), the other class more sensitive to travel time and cost (consisting of all other commodity types). The less cost-sensitive goods account for between 5% and 9% of all ton-miles shipped by trucks in the United States, so it was further concluded that the less cost-sensitive class could be dropped for the purposes of LOS estimation.

It was also noted that the average truck shipment times and shipment costs by commodity type by region derived from the FHWA FAF are almost all under 10 hours and under $1000, so the time and cost splines in the Cambridge model were dropped.

The original Cambridge model consequently can be streamlined to the following:

$$U = \alpha * (Reliability - 1) + \beta * Cost + \gamma * Time \quad \text{Equation 18}$$

where

U = perceived utility to shippers and carriers of a truck shipment of a single generic commodity type.

All other variables (reliability, cost, time) and coefficients (alpha, beta, gamma) are as defined in Exhibit 36.

6.3.4 Replacement of Commodity Shipment Costs with Average

If we replace the commodity-specific shipping costs with the average shipment cost of $750 for the Continental United States ($1,300 for Alaska and $100 for Hawaii), then the analyst no longer needs to acquire shipping cost information.

Exhibit 36. Coefficients for two commodity utility model (Equation 18).

Variable	Description	Coefficient	
Reliability	Probability of On-Time Arrival (0.00 – 1.00)	α	+5.00
Cost	Shipment Cost ($)	β	–0.01
Time	Average Shipment Time (hr)	γ	–0.32

6.3.5 Prorating Reliability Effects by Facility Length

During testing of the streamlined model, it was noted that it significantly overestimated the value of reliability, incorrectly suggesting that shippers would be willing to pay tolls of $10 to $30 per mile for 90% probabilities of on-time arrival. Upon re-evaluation of the Cambridge model, it was noted that the reliability effect applied to the entire shipment distance rather than just the facility length. Consequently, the reliability effect within the Cambridge model incorporated a distance component. It was decided to prorate the reliability effect of the facility according to the percent of the total trip length accounted for by the facility.

6.4 Streamlined Utility Model (Model 2)

The previous steps result in the following streamlined utility equation for Model 2:

$$U = 5.00 * \frac{L}{ASL} * (POTA - 1) - 0.01 * (ASC + Toll) - 0.32 * (AST + T_{FF}(TTI - 1)) \qquad \text{Equation 19}$$

where

U = Perceived utility to shippers and carriers of a truck shipment;
$POTA$ = Probability of on-time arrival;
L = Length of facility (miles);
ASL = Average shipment length (200 miles Continental U.S., 280 miles Alaska, 30 miles Hawaii);
ASC = Average shipment cost ($750 Continental U.S., $1,300 Alaska, $100 Hawaii);
$Toll$ = Toll paid by trucks to use facility ($);
AST = Average shipment time (3 hr Continental U.S., 5 hr Alaska, 0.5 hr Hawaii);
T_{FF} = Free-flow travel time to travel length of facility (hr);
TTI = Travel time index, ratio of mean truck speed for the given scenario to free-flow truck speed.

The proposed LOS index and the LOS thresholds using the streamlined utility model are the same as those for Model 1 [The LOS index is (Actual–Worst)/(Best–Worst), which is used in Exhibit 29].

6.5 Logistic Formulation with Truck Friendliness (Model 3)

The streamlined model (Model 2) requires that the LOS model be applied three times for each facility: once to compute the utility for ideal conditions, once for worst-case conditions, and once for actual conditions during the selected study period (such as the weekday P.M. peak period). While the ideal condition is relatively easy to identify (100% on-time arrival, free-flow speeds, and no tolls), the identification of worst-case conditions is less obvious. The absolute worst case of 0% on-time arrival, zero speed, and infinite tolls is not numerically tractable, so the agency must select a "realistic" worst case with relatively little guidance as to what is a reasonable "worst" case. This can be an advantage for agencies desiring to calibrate the truck LOS results to local conditions; this can be a disadvantage for agencies not willing or able to calibrate the results to local conditions.

An alternative approach was developed for estimating LOS from utility that avoids the need to explicitly identify a "worst-case condition." It employs a logistic function that is self-limiting to values between 0% and 100% (see Exhibit 37).

$$\%TLOS = \frac{1}{(1+\alpha e^{-\beta U(x)})} \qquad \text{Equation 20}$$

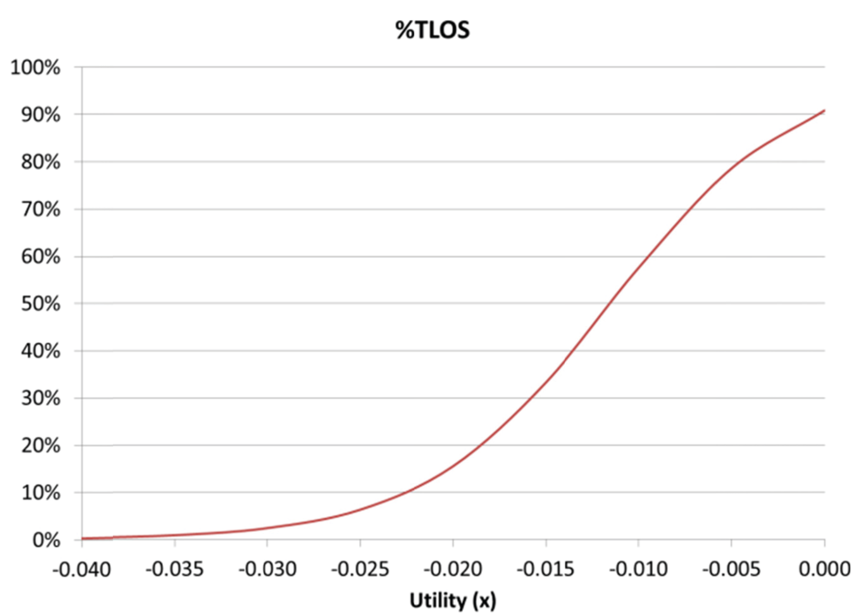
where

$\%TLOS$ = The truck LOS index as a percentage of ideal conditions.
α = Calibration parameter (determines value of %TLOS at $x = 0$). A value of 0.10 was selected heuristically so that model yields LOS A (>90% TLOS) under ideal reliable, free-flow, no toll conditions.
β = Calibration parameter (determines rate at which function increases to 100%). A value of 200 was selected heuristically so that model yields LOS F (<50% TLOS) if any one of these conditions is present: POTA <50%, TTI > 3.25, or Toll > $1.10/mile.
$U(x)$ = Utility function.

One of the desirable characteristics of a truck LOS model would be that it is not unduly influenced by the selection of facility length. Ideally, facilities of different lengths but with similar reliability and average operating speeds should get similar LOS ratings.

In Model 2, the effects of facility length were cancelled out by incorporating the utility calculations in both the numerator and the denominator of the truck LOS index. The logistic function used in Model 3 explicitly avoids the computation of multiple utilities for the same facility under

Exhibit 37. The %TLOS logistic function for Model 3.



best- and worst-case conditions; therefore, other methods must be explored to reduce the sensitivity of Model 3 to varying facility lengths.

Revisiting the utility function in Model 2 (Equation 19) it can be noted that the free-flow travel time is facility length divided by the free-flow speed. The toll in that equation can be replaced with toll/mile times the facility length. These substitutions allow us to divide the equation by the facility length without changing the relative effects of reliability, speed, and tolls on the utility. We obtain the following utility equation:

$$U = \frac{5}{ASL} * (POTA - 1) - 0.01 * (ASC/L + Toll/mi) - 0.32 * \left(AST/L + \frac{(TTI - 1)}{FFS}\right) \qquad \text{Equation 21}$$

where

U = Perceived utility to shippers and carriers of truck shipments using the facility;
$POTA$ = Probability of on-time arrival;
L = Length of facility (miles);
ASL = Average shipment length (200 miles Continental U.S., 280 miles Alaska, 30 miles Hawaii);
ASC = Average shipment cost ($750 Continental U.S., $1,300 Alaska, $100 Hawaii);
$Toll/mi$ = Toll rate paid by trucks to use facility ($/mile);
AST = Average shipment time (3 hr Continental U.S., 5 hr Alaska, 0.5 hr Hawaii);
FFS = Free-flow speed for trucks on facility (mph); and
TTI = Travel time index, ratio of mean truck speed for the given scenario to free-flow truck speed.

Grouping the facility length sensitive factors together, we get

$$U = \frac{5}{ASL} * (POTA - 1) - 0.01 * \left(\frac{Toll}{mi}\right) - 0.32 * \left(\frac{(TTI - 1)}{FFS}\right) - (0.01 * ASC + 0.32 * AST)/L \qquad \text{Equation 22}$$

Sensitivity testing of Equation 22 for facilities between 1 and 10 miles in length found that the facility length dependent term (incorporating average shipping cost and average shipping time) caused the predicted LOS to be highly sensitive to the facility length. In addition, the average shipping cost (being in the hundreds of dollars range) tended to dominate the utility, significantly reducing its sensitivity to changes in reliability, and the travel times. The facility length dependent term of the utility equation was consequently dropped from further consideration.

This last change also had the advantage of reducing the data requirements for the LOS model. Average shipping cost and average shipping time would no longer be required by the model. The result is the following utility equation for Model 3:

$$U = \frac{5}{ASL} * (POTA - 1) - 0.01 * (Toll/mi) - 0.32 * \left(\frac{(TTI - 1)}{FFS}\right) \qquad \text{Equation 23}$$

where

$U(x)$ = Perceived utility of truck shipments using the facility;
$POTA$ = Probability of on-time arrival;
ASL = Average shipment length (200 miles Continental U.S., 280 miles Alaska, 30 miles Hawaii);

Toll/mi = Toll rate paid by trucks to use facility ($/mile);
FFS = Free-flow speed for trucks on facility (mph); and
TTI = Travel time index, ratio of mean truck speed to free-flow truck speed.

For example, for the Continental United States, the equation is

$$U(x) = 0.025 * (POTA - 1) - 0.01 * \frac{Toll}{mi} - 0.32 * \left(\frac{(TTI - 1)}{FFS}\right) \qquad \text{Equation 24}$$

At one of the public agency workshops conducted to review the candidate models, several of the freight planning experts requested that the truck LOS model also include a "truck friendliness index" to indicate the degree to which substandard geometry, structures, or at-grade railroad crossings hindered the ability of legal trucks with legal loads from using the facility without having to slow down for a railroad crossing or to maneuver through a geometric construction.

The truck friendliness index (TFI) was consequently added to Model 3 to enable agencies to incorporate geometric limitations and at-grade rail crossing features of the facility into the truck LOS. The TFI is set at 1.00 for a facility designed and built to accommodate all federal, state, and local legal vehicles and loads with no at-grade railroad crossings. This value of 1.00 is depreciated at the agency's discretion to account for vehicle length, width, height, turning radius, and load restrictions on truck usage of the facility. The model has been calibrated so that a TFI of 0.60 will yield LOS F in the model, regardless of the reliability, travel time, or toll on the facility.

Adding the truck friendliness index to Equation 23, Model 3 can be re-specified as

$$U(x) = A * (POTA - 1) + B * (TTI - 1) + C * (Toll/mi) + D * (TFI - 1) \qquad \text{Equation 25}$$

where

U(x) = Utility of facility for truck shipments.
A, B, C = Calibration parameters from Model 2:
$A = 5/ASL$,
$B = -0.32/FFS$,
$C = -0.01$
where *ASL* = average shipment length (200 miles Continental U.S., 280 miles Alaska, 30 miles Hawaii) and FFS = Free-flow speed (mph).
D = Calibration parameter = 0.03 (determined heuristically so that LOS F if TFI is below 0.60).
POTA = Probability of on-time arrival, with on-time being defined as a TTI of 1.33 or less for freeways, multilane highways, and two-lane highways; for urban streets, TTI ≤3.33.
TTI = Travel time index for study period, ratio of free-flow speed to actual speed.
Toll/mi = Truck toll charged per mile ($/mi).
TFI = Truck friendliness index (1.00 = no constraints or obstacles to legal truck load and vehicle usage of facility, 0.00 = no trucks can use facility).

6.6 Reliability and Friendliness (Model 4)

A fourth LOS model was created to address requests for a travel-time-reliability-only model while retaining the TFI desired by workshop participants. It was pointed out by the Philadelphia workshop participants that Model 3 and its ancestor models appeared to double count reliability by incorporating both probability of on-time arrival and the TTI, with both being measured against the same standard—the free-flow speed.

This model is obtained by dropping tolls and the TTI portions of the utility equation from Model 3. The logistic function and parameters of Model 3 are retained. The utility function is reformulated to create Model 4 as follows:

$$U(x,6) = A*(POTA - 1) + D*(TFI - 1) \qquad \text{Equation 26}$$

where

$U(x,6)$ = Utility function for Model 4;
A = Calibration parameter from Model 3 ($A = 0.025$);
D = Calibration parameter = 0.03 (determined heuristically so that LOS F if TFI is below 0.60);
$POTA$ = Probability of on-time arrival, with on-time being defined as a TTI of 1.33 or less; and
TFI = Truck friendliness index (1.00 = no constraints or obstacles to legal truck load and vehicle usage of facility, 0.00 = all trucks unable to use facility).

6.7 Results of Review by Public Agencies

The four truck LOS models were reviewed by 28 public agency and university freight planning experts in Philadelphia, Pennsylvania, and by 33 public agency freight planning experts in Sacramento, California. Public agency representatives came from state DOTs, MPOs, port authorities, and city and county planning agencies.

The workshop participants had the following comments and conclusions about the four proposed LOS models:

- The workshop participants agreed that truck LOS will be a useful tool to help make goods-movement projects related to trucks more competitive with other transportation improvement projects. It should help "getting trucks into the planning process":
  - Truck LOS will be useful for MAP-21, for communicating to the general public, and for decisionmakers,
  - Truck LOS should be measurable,
  - Truck LOS should quantify different degrees of LOS F, and
  - Truck LOS should be calibratable to local conditions and perceptions.
- The general preference of workshop participants was for Model 3 (Reliability, Speed, Cost, Friendliness) with the ability to calibrate it to local perceptions; they liked the ability to include tolls if they were an issue and felt it easy to exclude tolls if they were not an issue: "Better to have it and not use it, than to not have it."
- Model 4 (Reliability only plus Friendliness) was second favorite.
- Models 1 and 2 were generally least desired; the primary objections appeared to be their greater apparent complexity.

6.8 Recommended Truck LOS Model

The recommended truck LOS model is Model 3—combining speed, reliability, cost, and truck friendliness in a logistic model formulation (Equation 25).

SECTION 7

Truck Level-of-Service Case Studies

This section presents example applications of the recommended truck LOS model and framework in several case studies. These case studies illustrate the application of three of the truck LOS models considered in the prior section:

- Model 2—The Streamlined Utility Model,
- Model 3—The Logistic Model with Truck Friendliness Index, and
- Model 4—A Reliability Plus Friendliness Model.

In all cases, it is assumed that the analyst has estimated truck speeds and reliability using one or more appropriate methodologies. The following sections describe recommended methodologies for making these estimates.

7.1 Study Site 1—California Class I Interstate Freeway

The application of three of the truck LOS models is illustrated for a 20-mile-long section of a major interregional Interstate freeway in California. The high volume of trucks and the fact that this freeway is a critical inter-regional link between the San Francisco Bay Area and the San Joaquin Valley makes this a Class I facility for truck LOS purposes. The study section is split into two segments (one mountainous, the other level). The selected study period is the 7–9 A.M. peak period.

Exhibit 38 shows the facility-specific data required by the truck LOS models.

7.1.1 Case Study 1.1—Computation of Existing Truck LOS

In this case study, the truck LOS is computed using three candidate LOS models for two segments of the Site 1 freeway: one in mountainous terrain and the other on level terrain. See Exhibit 39.

Model 2—Streamlined Utility Model

For Segment 1, the free-flow utility is computed using Equation 24, a length of 8.9 miles, a probability of on-time arrival of 90%, a toll of zero dollars, and a TTI of 1.00. The resulting free-flow utility for Segment 1 is –8.49. The worst case utility is computed using the same equation with a policy speed of 10 mph and probability of on-time arrival of 10% for the facility. The worst case utility is –9.01.

The *actual* utility for Segment 1 is computed using the same equation and length, but with a 10% probability of on-time arrival and a 36.9 mph actual speed. The actual utility is –8.75. The difference between the actual and the ideal utilities is 0.26, which is about 50% of the difference between best utility and the worst utility. The actual utility is thus LOS F according to the scale given in Exhibit 29. The computations for Segment 2 proceed similarly.

Exhibit 38. Data for Case Studies 1.1 and 1.2.

Data Item	Segment 1	Segment 2
Length	11.1 miles	8.9 miles
Terrain	Mountainous	Level
Major Grades (% Grade, Length)	3% up, 4.2 miles 3% down, 2.3 miles	None
Max/Min (Best/Worst) Speeds	65/10 mph	65/10 mph
Actual Speed (A.M. Peak Period)	36.9 mph	42.3 mph
Best/Worst Probability of On-Time Arrival	90%/10%	90%/10%
Probability of On-Time Arrival	10%	60%

Note: Best/worst speeds and probability of on-time arrival are set by agency policy for the facility.

Model 3—Logistic Model with Friendliness Index

Model 3 uses the actual probability of on-time arrival, TTI, and toll. The "ideal" free-flow reliable condition is incorporated in the variables it uses (POTA-1, and 1-TTI). It does not require the worst-case conditions to estimate LOS. Model 3 requires a truck friendliness assessment, which is not required by Model 2. In this case, the facility is an Interstate freeway designed to modern standards; thus, the TFI is set at 1.00.

Model 4—Reliability and Friendliness Logistic Model

Model 4 does not require the toll or TTI information required by Models 2 and 3. Like Model 3, Model 4 also requires a truck friendliness assessment. The TFI is identical to that for Model 3.

Comparison of LOS Model Results for Case Study 1.1

The truck LOS results for the facility using each of the three LOS models are compared in Exhibit 40. All three models agree that Segment 1 (the long-grade section) is operating at LOS F for trucks. The models disagree regarding the truck LOS for Segment 2: Model 2 says it is C, Model 3 says it is F, and Model 4 says it is E (but not too far from the LOS E/F threshold).

Exhibit 39. Study section for Case Studies 1.1 and 1.2.

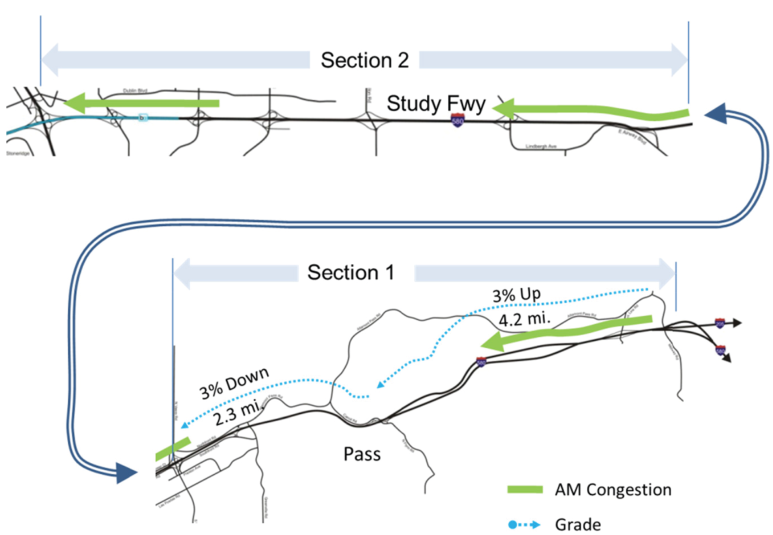


Exhibit 40. Comparison of LOS model results for example application facility.

	Segment 1	Segment 2
Model 2 – Streamlined Utility Model LOS	F	C
Percent of ideal	50%	78%
Model 3 – Logistic LOS Model	F	F
Percent of ideal	5%	44%
Model 4 – Reliability and Friendliness LOS	F	E
Percent of ideal	10%	58%

Note that Models 3 and 4 find a greater difference in performance between Segments 1 and 2 than is found by Model 2 as evidenced by the wider range in indices (percent ideal) output by Models 3 and 4 than by Model 2.

7.1.2 Case Study 1.2—Sensitivity Tests

Segment 1 from Case Study 1.1 was selected for sensitivity testing. The effects of changing the state in which the facility is located are shown in Exhibit 41. This exhibit also shows the effect on the letter grade truck LOS of the facility class (Class I or Class III). Model 2 would rate the segment at LOS D if it were a Class III facility located in Alaska. Otherwise, the models all agree that the segment would rate LOS F regardless of class or location in United States.

Arbitrarily shortening or lengthening Segment 1 from Case Study 1.1 had no effect on the results produced by Models 2, 3, and 4.

As shown in Exhibit 42, reliability has a significant effect on the computed truck LOS. This test was performed on both segments from Case Study 1.1.

Model 2 would rate both segments at LOS A if reliability were improved to 90% probability of on-time arrival. Model 4 would rate both at LOS B with improved reliability. Model 3 would rate both segments at LOS C. All three models show similarly large sensitivities to reliability. Reliability has a slightly greater effect on the TLOS indices in Models 3 and 4 than for Model 2.

Exhibit 41. Effect of region and facility class on Models 2, 3, and 4 results.

	Facility Class					
	Class I			Class III		
State	Model 2	Model 3	Model 4	Model 2	Model 3	Model 4
Continental U.S.	F (50%)	F (5%)	F (10%)	F (50%)	F (5%)	F (10%)
Alaska	E (56%)	F (16%)	F (29%)	D (56%)	F (16%)	F (29%)
Hawaii	F (15%)	F (0%)	F (0%)	F (15%)	F (0%)	F (0%)

Note: The test segment is an 11.1-mile segment from Case Study 1.1. All variables held constant except region.

Exhibit 42. Effect of reliability on Models 2, 3, and 4 results.

	Segment 1	Segment 2
Original/Improved On-Time Arrival	10%/90%	60%/90%
Model 2 – Streamlined Utility Model LOS		
Original/Improved LOS (%TLOS)	F (50%)/A (92%)	C (78%)/A (94%)
Model 3– Logistic LOS Model		
Original/Improved LOS (%TLOS)	F (5%)/C (74%)	F (44%)/C (78%)
Model 4 – Reliability and Friendliness LOS		
Original/Improved LOS (%TLOS)	F (10%)/B (86%)	E (58%)/B (86%)

Note: The test segments are from Case Study 1.1; all variables held constant except probability of on-time arrival.

7.2 Study Site 2—Virginia Class I Interregional Freeway

The second study site for case studies is a 29.4-mile-long section of the Interstate freeway in Virginia (see Exhibit 43). This is a high-truck-volume, critical, interregional facility that is rated by the agency as a Class I facility for truck LOS analysis purposes. The selected study period is the weekday 6–10 A.M. peak period.

7.2.1 Case Study 2.1—Predict the Effects of High-Occupancy-Vehicle Lane on Truck LOS

This case study involves predicting the effects on northbound A.M. peak-period truck LOS of a project adding a third northbound HOV lane to the Interstate freeway. The number of

Exhibit 43. Study Site 2—Class I facility in Virginia.

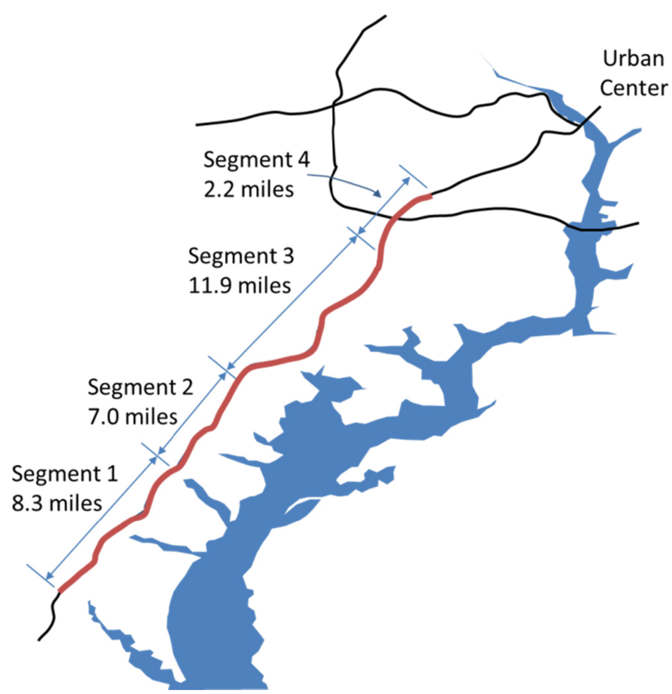


Exhibit 44. Case Study 2.1 input data.

Segment Characteristics	Segment 1	Segment 2	Segment 3	Segment 4
Length (miles)	8.3	7.0	11.9	2.2
Policy Best/Worst Speed (mph)	65/10	65/10	65/10	65/10
Existing Speed (mph)	53	48	46	42
Future Speed (mph)	58	55	53	51
Policy Best/Worst Probability On-Time	90%/10%	90%/10%	90%/10%	90%/10%
Existing Probability On-Time	50%	38%	35%	33%
Future Probability On-Time	83%	65%	55%	48%

HOV lanes will be expanded from two to three, and those HOV lanes will be converted to high-occupancy-toll (HOT) operation.

While the mainline mixed flow lanes are not undergoing any capacity expansion or improvements, with the addition of a third HOV lane and an expansion of service to include both HOV and HOT customers, it is expected that the reduction in vehicles using the mixed flow lanes during the morning peak period will benefit freight traffic in the area.

A combination of travel demand forecasting and traffic operations models is used to estimate existing and future mixed flow lane mean speeds for the four segments. A methodology such as that developed by the SHRP2-L08 project (Kittelson and Vandehey, 2012) is used to estimate existing and future weekday A.M. peak-period travel time distributions for the segments. The input data are shown in Exhibit 44.

The truck LOS results using each of the LOS models are compared in Exhibit 45 for existing conditions and future conditions. The models all agree on the trend of improvement for truck LOS caused by adding the HOV lane. Model 2 shows the most extreme improvement of the models for Segment 1, going from LOS E to A. Model 3 is slightly more conservative than the other models, often rating the segments one letter grade poorer than Models 2 and 4.

7.2.2 Case Study 2.2—Effects of Tolling on Truck LOS

One option being considered for better managing traffic congestion on the I-95 freeway is congestion pricing for the full facility. The question is how much is reliability worth to the shippers and carriers using the freeway? Only Models 2 and 3 (which are sensitive to price) can be applied to this case study.

Since this case study is to determine the value to shippers and carriers of improved reliability on the freeway, the reliability is improved to an 85% probability of on-time arrival and then the

Exhibit 45. Comparison of LOS models for adding HOV lane to Class I freeway.

	Segment 1	Segment 2	Segment 3	Segment 4
Model 2 – Streamlined Utility				
Exist/Future LOS (%TLOS)	C(76%)/A(95%)	D(69%)/B(85%)	D(66%)/C(79%)	D(64%)/C(75%)
Model 3– Logistic LOS Model				
Exist/Future LOS (%TLOS)	F(40%)/C(79%)	F(24%)/E(59%)	F(21%)/F(46%)	F(17%)/F(36%)
Model 4 – Reliability/Friend				
Exist/Future LOS (%TLOS)	F(45%)/B(81%)	F(31%)D(63%)	F(28%)/E(51%)	F(26%)/F(43%)

Exhibit 46. Results for Case Study 2.2.

Segment	Original Reliability, No Toll			Good Reliability, No Toll			Good Reliability, Toll		
	POTA	Toll	LOS	POTA	Toll	LOS	POTA	Toll	LOS
	Model 2								
1	83%	$0	A(95%)	85%	$0	A(96%)	85%	$0.25	A(95%)
2	65%	$0	B(85%)	85%	$0	A(95%)	85%	$3.50	B(85%)
3	55%	$0	C(79%)	85%	$0	A(95%)	85%	$9.00	C(79%)
4	48%	$0	C(75%)	85%	$0	A(94%)	85%	$2.00	C(75%)
Total								$14.75	
	Model 3								
1	83%	$0	C(79%)	85%	$0	B(81%)	85%	0.50	C(79%)
2	65%	$0	E(59%)	85%	$0	C(80%)	85%	$3.50	E(59%)
3	55%	$0	F(46%)	85%	$0	C(79%)	85%	$8.75	F(46%)
4	48%	$0	F(36%)	85%	$0	C(78%)	85%	$2.00	F(37%)
Total								$14.75	

Note: Model 4, since it lacks a toll component, cannot be used for such a test.

new utility and LOS compared with the no-toll condition. The toll is then added to the cost of the shipments on each segment until the original utility is obtained. Exhibit 46 summarizes the results by segment.

Both models value an 85% probability of on-time arrival (reliability) at $14.75 for the 29.4-mile facility—approximately 50 cents per mile. This agreement between the two models is to be hoped for since both models incorporate the same cost parameters, although they employ different functional forms.

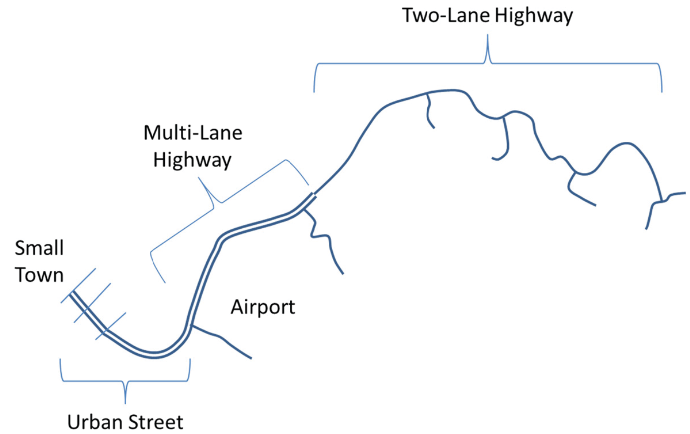
7.3 Study Site 3—Urban/Rural Highway

The third study site is a 16.6-mile-long section of highway that extends from a small town to a nearby airport and then continues on to serve an agricultural area. The highway is a mix of urban arterial, multilane highway, and two-lane rural highway (see Exhibit 47). It starts out as a four-lane signalized urban street within a small town, then transitions to a four-lane divided highway between the town and its airport. Beyond the airport, the multilane highway becomes a two-lane rural highway. The selected study period is the weekday 4–6 P.M. peak period.

7.3.1 Case Study 3.1—Assess LOS for Urban/Rural Highway with Growth

The highway is a locally important connector between the local population center, its airport, and agricultural areas beyond the airport. The portion between the small town and the airport is rated Class II by the agency. The portion beyond the airport is rated Class III.

Exhibit 47. Case Study 3 site.



The state DOT is anticipating a shift from primarily agricultural crops on this highway to a mix of electronics and agricultural goods with higher intensities of traffic associated with light industry. As a result, this highway is being evaluated by the state to determine its ability to continue to provide acceptable freight LOS as the area continues to develop.

Exhibit 48 shows existing conditions, and Exhibit 49 shows future conditions. Exhibit 50 shows the existing TTI distribution for the highway segments. The TFI is set by the agency at 0.75 on the two-lane highway section to reflect an at-grade railroad crossing and load limits on a couple of bridges on the highway.

For urban streets, a larger tolerance of 3.33 TTI for on-time arrival is set because the HCM definition of free-flow speed on urban streets excludes all signal delay (causing a wide disparity between the posted midblock speed limit and the actual achievable through-speed on the street even in low-flow conditions). For multilane and two-lane highways, the original 1.33 TTI tolerance for on-time arrival is retained.

Exhibit 48. Case Study 3.1 data—existing conditions.

Truck LOS Input Data	Segment 1	Segment 2	Segment 3	Segment 4
Truck Facility Type	Class II	Class II	Class III	Class III
HCM Facility Type	Urban Street	Multilane Hwy	Multilane Hwy	2-Lane Hwy
Limits	First Street to City Limits	City Limits to Airport	Airport to 2-Lane	Multilane to End of Highway
Length	0.6	2.3	3.8	9.9
Free-Flow Speed (mph)	35	55	55	45
Worst Speed (mph)	10	10	10	10
Actual Speed (mph)	12	42	43	37
85% TTI	3.27	1.39	1.35	1.32
Best POTA	90%	90%	90%	90%
Worst POTA	10%	10%	10%	10%
Actual POTA	85%	70%	90%	95%
Truck Friendliness Index	1.00	1.00	1.00	0.75

Notes: POTA = probability of on-time arrival; TTI = travel time index.

Exhibit 49. Case Study 3.1 data—future conditions.

Truck LOS Input Data	Segment 1	Segment 2	Segment 3	Segment 4
Truck Facility Type	Class II	Class II	Class III	Class III
HCM Facility Type	Urban Street	Multilane Hwy	Multilane Hwy	2-Lane Hwy
Limits	First Street to City Limits	City Limits to Airport	Airport to 2-Lane	Multilane to End of Highway
Length (miles)	0.6	2.3	3.8	9.9
Free-Flow Speed (mph)	35	55	55	45
Worst Speed (mph)	10	10	10	10
Actual Speed (mph)	10.8	40.7	41.7	35.4
85% TTI	3.68	1.44	1.40	1.42
Best POTA	90%	90%	90%	90%
Worst POTA	10%	10%	10%	10%
Prob. On-Time Arrival	60%	50%	70%	75%
Truck Friendliness Index	1.00	1.00	1.00	0.75

Notes: POTA = probability of on-time arrival; TTI = travel time index.

Exhibit 51 shows how the existing and future truck LOS results vary by segment by truck LOS model. The models are in general agreement as to trends in truck LOS. All show truck LOS worsening in the future:

- For Segment 1—the urban street segment with a high probability of on-time arrival (85%) but a low mean speed of 12 mph in comparison with the midblock free-flow speed of 35 mph—is rated LOS B for existing conditions by Model 4. Models 2 and 3, however, rate this segment at LOS E/F for existing conditions due to the low mean speed on the segment (which Model 4 does not include). For future conditions on this street segment, all three models agree at rating Segment 1 at LOS F. This is primarily due to the degradation in reliability for this segment in the future.

Exhibit 50. Case Study 3.1 TTI distributions—existing conditions.

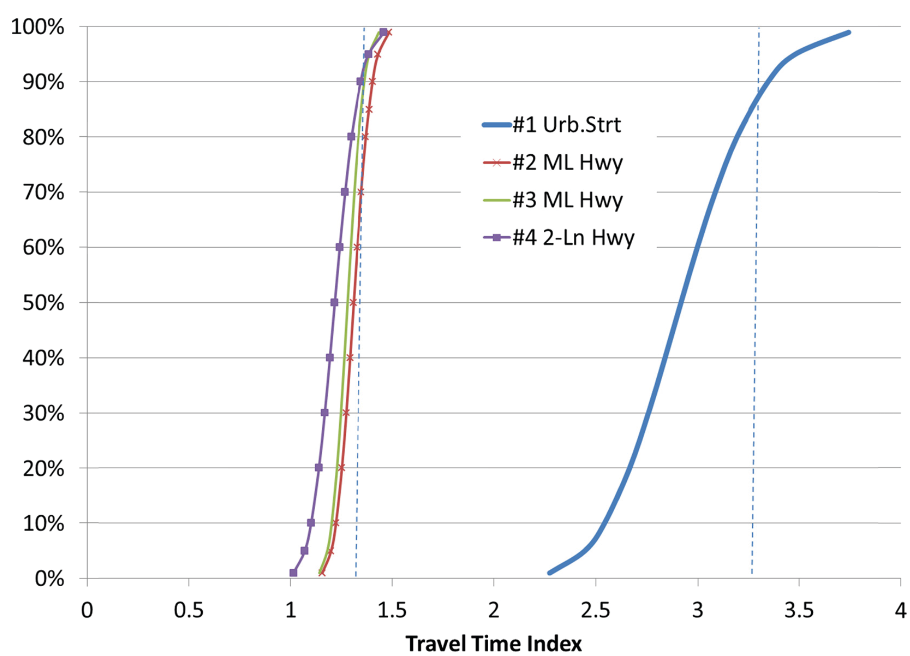


Exhibit 51. Comparison of LOS model results for Case Study 3.1.

	Segment 1	Segment 2	Segment 3	Segment 4
Model 2 – Streamlined Utility				
Exist/Future LOS (%TLOS)	D(56%)/F(35%)	A(85%)/C(74%)	A(96%)/A(85%)	A(99%)/A(87%)
Model 3– Logistic LOS Model				
Exist/Future LOS (%TLOS)	F(12%)/F(1%)	D(61%)/F(35%)	A(81%)/C(61%)	D(56%)/F(30%)
Model 4 – Reliability/Friend				
Exist/Future LOS (%TLOS)	B(83%)/F(43%)	C(69%)/E(45%)	A(86%)/C(69%)	C(63%)/F(39%)

- Model 3 appears to be the most conservative among the three models in rating the truck LOS for all 4 segments under both existing and future conditions.
- Model 2 rates Segment 4 (the two-lane highway segment) as LOS A under existing conditions, primarily because of the excellent probability of on-time arrival (95%). The other two models rate this segment at LOS C/D, primarily because of the TFI for this segment, which is not taken into consideration in Model 2.

SECTION 8

Prediction of Freeway Truck Speeds

Section 8 focuses on development of improved methodologies for predicting the speeds of trucks on freeways under varying vertical grade conditions.

8.1 Existing HCM Treatment of Trucks on Freeways

The current HCM freeway procedures are not designed to predict truck speeds on freeways. The current HCM freeway procedures use passenger car equivalent (PCE) values to create equivalent passenger-car-only flow rates corresponding to the observed mixed vehicle flow rates. This transformation leads to performance metrics (e.g., density and speed) based on automobile-only flow conditions that are asserted to pertain to the mixed flow condition—that is, the PCE values produce passenger-car-only flow rates that have densities (the LOS measure) and overall average traffic speeds that are consistent with those that would result from the actual flow rates and traffic (especially truck) mixes. There is no provision in the HCM for predicting truck speeds separately from that of mixed flow traffic.

So that HCM users do not have to develop PCE values for every analysis situation, the HCM presents suggested values for a variety of conditions. Exhibit 52 shows the values suggested for freeway analyses in level, rolling, and mountainous terrain.

A more expansive set of suggested values is provided for specific conditions, as shown in Exhibit 53. This table gives PCE values for combinations of grade, grade length, and heavy-vehicle percentage. For example, a PCE of 3.0 is recommended for a 5–6% grade of length 0.75–1.00 mile where the percentage of trucks and buses is 20%.

The HCM presents a graph that shows how truck speeds vary for different segment lengths, grades, and starting speeds (see Exhibit 54). The graph is nominally predicated on a truck with a weight-to-horsepower ratio of 200 lbs/hp entering an upgrade at 55 mph or accelerating from 8 mph on either an upgrade or a downgrade. Otherwise, no information about truck speeds is given in any of the HCM procedures. Rather, the HCM reports an average speed for the traffic stream as a whole. Moreover, that speed is technically for a PCE traffic stream. Hence, if the trucks have a different speed, that speed is not identified.

8.2 Research Objective and Approach

The objective of this task within the research project was to develop a methodology for predicting truck speeds on freeways under varying vertical grade conditions. This methodology has been developed using a seven-step process:

1. Conduct a preliminary analysis of available field observation of freeway performance to gain a sense of what should emerge from the methodological development.

Exhibit 52. PCE values for trucks, buses, and RVs.

Passenger Car Equivalent	Level Terrain	Rolling Terrain	Mountainous Terrain
E_T (trucks and buses)	1.5	2.5	4.5
E_R (RVs)	1.2	2.0	4.0

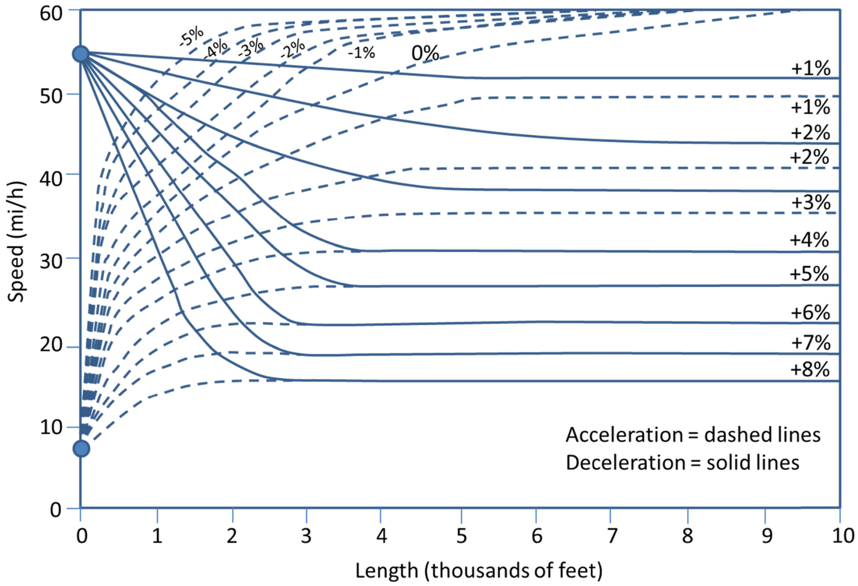
Source: Exhibit 11-10, *Highway Capacity Manual* (TRB, 2010).

Exhibit 53. PCEs for specific grades.

		Proportion of Trucks and Buses								
Upgrade(%)	Length (mi)	2%	4%	5%	6%	8%	10%	15%	20%	≥25%
≤2	All	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
>2–3	0.00–0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.25–0.50	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.50–0.75	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.75–1.00	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5
	>1.00–1.50	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	>1.50	3.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0
>3–4	0.00–0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.25–0.50	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	>0.50–0.75	2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	>0.75–1.00	3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0
	>1.00–1.50	3.5	3.5	3.0	3.0	3.0	3.0	2.5	2.5	2.5
	>1.50	4.0	3.5	3.0	3.0	3.0	3.0	2.5	2.5	2.5
>4–5	0.00–0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.25–0.50	3.0	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	>0.50–0.75	3.5	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.5
	>0.75–1.00	4.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.0
	>1.00	5.0	4.0	4.0	4.0	3.5	3.5	3.0	3.0	3.0
>5–6	0.00–0.25	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.25–0.30	4.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	>0.30–0.50	4.5	4.0	3.5	3.0	2.5	2.5	2.5	2.5	2.5
	>0.50–0.75	5.0	4.5	4.0	3.5	3.0	3.0	3.0	3.0	3.0
	>0.75–1.00	5.5	5.0	4.5	4.0	3.0	3.0	3.0	3.0	3.0
	>1.00	6.0	5.0	5.0	4.5	3.5	3.5	3.5	3.5	3.5
>6	0.00–0.25	4.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	1.0
	>0.25–0.30	4.5	4.0	3.5	3.5	3.5	3.0	2.5	2.5	2.5
	>0.30–0.50	5.0	4.5	4.0	4.0	3.5	3.0	2.5	2.5	2.5
	>0.50–0.75	5.5	5.0	4.5	4.5	4.0	3.5	3.0	3.0	3.0
	>0.75–1.00	6.0	5.5	5.0	5.0	4.5	4.0	3.5	3.5	3.5
	>1.00	7.0	6.0	5.5	5.5	5.0	4.5	4.0	4.0	4.0

Source: Exhibit 11-11, *Highway Capacity Manual* (TRB, 2010).

Exhibit 54. Performance curves for 200 lb/hp truck.



Source: Exhibit 11-A1, *Highway Capacity Manual* (TRB, 2010).

2. Select a test site with a calibrated microsimulation model for investigating the relationship between volumes, truck percentages, the mix of truck types, and vertical grade on sustained automobile and truck speeds.
3. Develop acceleration functions (acceleration versus speed, one for each truck type) that can be used as inputs into the microsimulation model so that the effects on truck speed could be tested for various grades, truck percentages, and mixes of semitrailer and single-unit trucks. Compare the trajectory predictions (speed versus distance) from these functions with those from prior studies.
4. Develop and apply a microsimulation model of a single-lane freeway with a constant grade to see whether any model parameter values need to be adjusted to generate speed-distance trajectories that are consistent with the findings from Steps 1 and 2 above. The use of a single-lane simulation at this point eliminates possible passing effects on the observed average link speed.
5. Conduct simulations of a wide range of truck types, weight-to-horsepower ratios, truck percentages, flow rates, and grades using a simulation model of a three-lane freeway with constant grades. Do this initially for one truck type (focused principally on FHWA Classes 5 and 9) and then for mixes of truck types and weight-to-horsepower ratios. The use of three-lane simulation at this point allows vehicle passing effects to be incorporated into the results.
6. Determine what predictive relationships can be used for truck PCEs and speeds based on the data from Step 4.
7. Test the resulting treatments for truck PCEs and speeds using a quasi-real case study whose setting is based on a real-world facility, but whose design and traffic mix details have been treated parametrically to allow tests of the effects of various other conditions (e.g., flow rates, truck mix percentages, and grades).

The findings from this process are described below.

8.3 Initial Field Assessment

Freeway performance for different truck percentages was examined based on data from I-40 in Raleigh, North Carolina. The intent was to gain a sense of what the methodology should predict. This stretch of freeway is basically level, it is three-lanes wide in each direction, and its geometry is consistent with the ideal conditions employed in the HCM.

Exhibit 55 shows a plot of the 15-min observations of flow and density. It is obvious that the truck percentage does have an effect on both the maximum flow rate that is achieved and the density that corresponds to that maximum flow rate. The maximum flow rates are lower and the densities are higher than those that arise when the truck percentage is less than 5%.

The plot also shows that the freeway speeds are influenced by the truck percentage. As is well known, the slope of the line from the origin to any data point is the speed that pertained when that data point was recorded. Hence, it appears that the interplay of the trucks with other vehicles creates slower speeds, higher densities, and lower capacities than for (nearly) all-automobile conditions.

Exhibit 56 shows a plot of the corresponding 15-min observations of speed and flow. In this case, the data points for different truck percentages are shown in separate graphs.

The most significant observation from Exhibit 56 is perhaps that the percentage of trucks has an influence on the speeds achieved at or near capacity. This is consistent with the insights emerging from the flow-density plot. Since this section of freeway is basically level, grade cannot be the cause. It must be the interaction of the trucks with the other vehicles. This effect may arise more generally; not just here.

The second observation is that the percentage of trucks has an influence on the 15-min average speeds during times of low flow. Since vehicle interactions are not likely to be the cause—it may be that the trucks using the freeway when the volume-to-capacity (V/C) ratio is low cannot or choose not to travel at the speed of the other vehicles.

These trends suggest that the influence of the trucks may be significant, especially at higher truck percentages. Moreover, the trucks are likely to affect both speed and density across the range of V/C ratios. Particularly, higher truck percentages are likely to result in higher densities and lower speeds than those that typify predominantly automobile conditions.

Exhibit 55. Flow-density relationships on I-40 for various truck percentages.

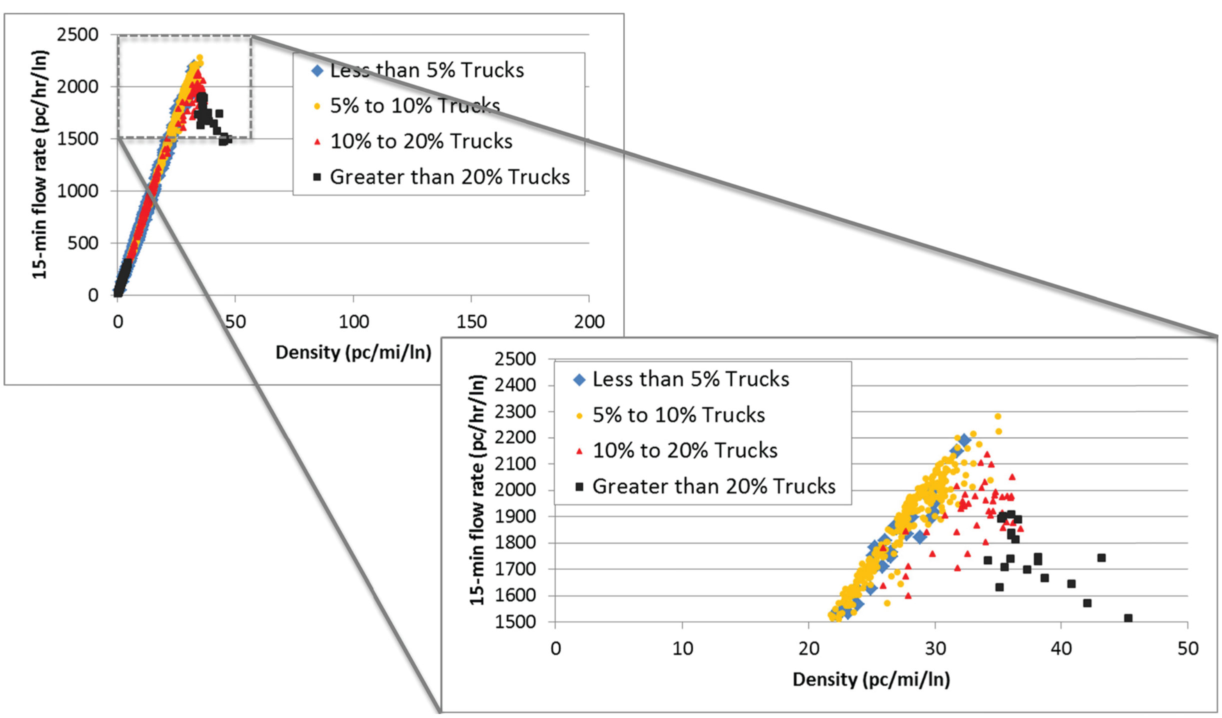
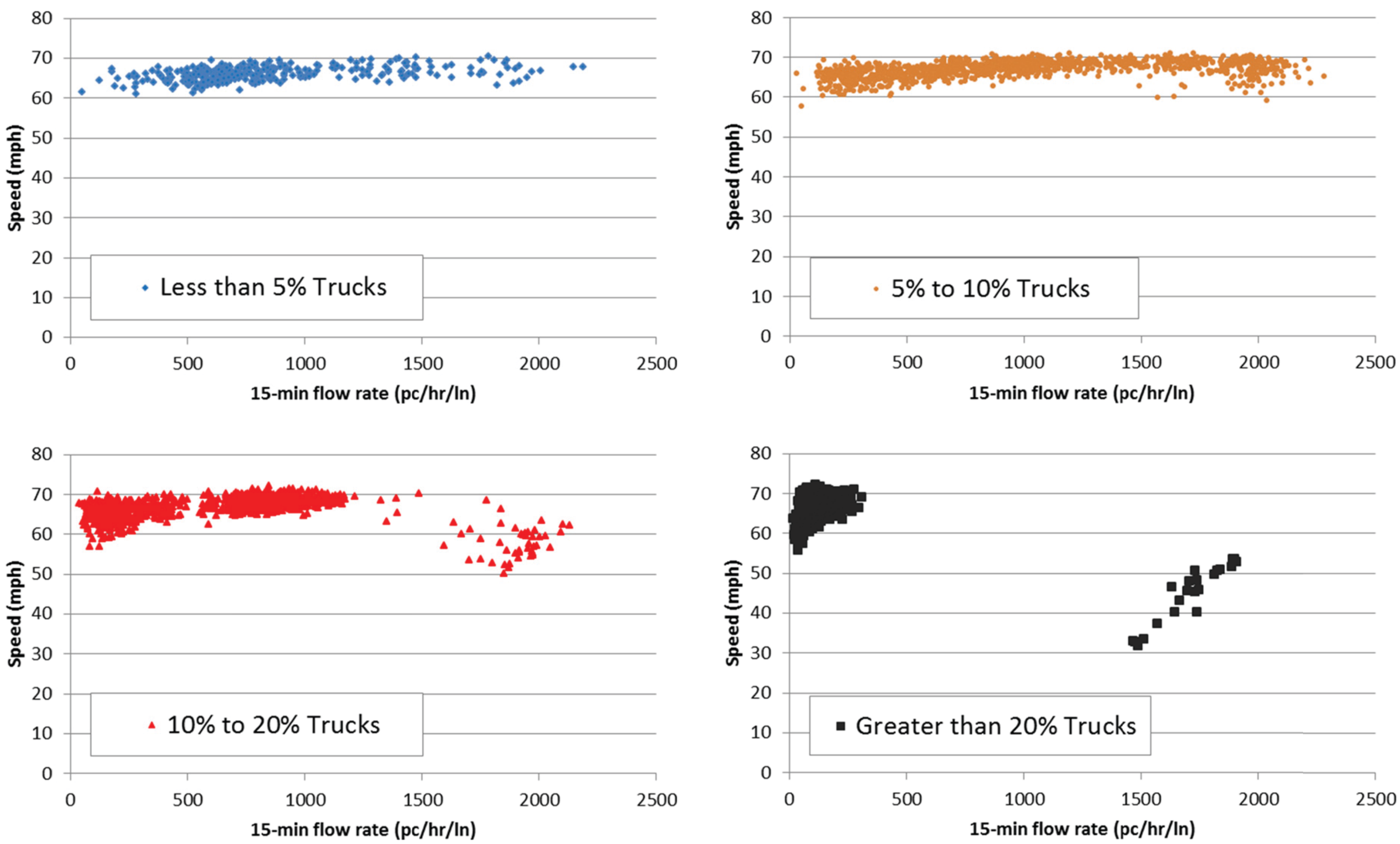


Exhibit 56. Speed-flow relationships on I-40 for various truck percentages.



8.4 The Freeway Test Bed

The investigation of the freeway speed flow effects of trucks on extended grades was performed on a hypothetical facility consisting of 8 miles of level three-lane freeway followed by 5 miles of three-lane freeway with a grade. The grade on the 5-mile section varied from –6% to +6% in 1% increments (13 grades total). The hypothetical facility was simulated using the VISSIM microsimulation model (PTV Group, n.d.).

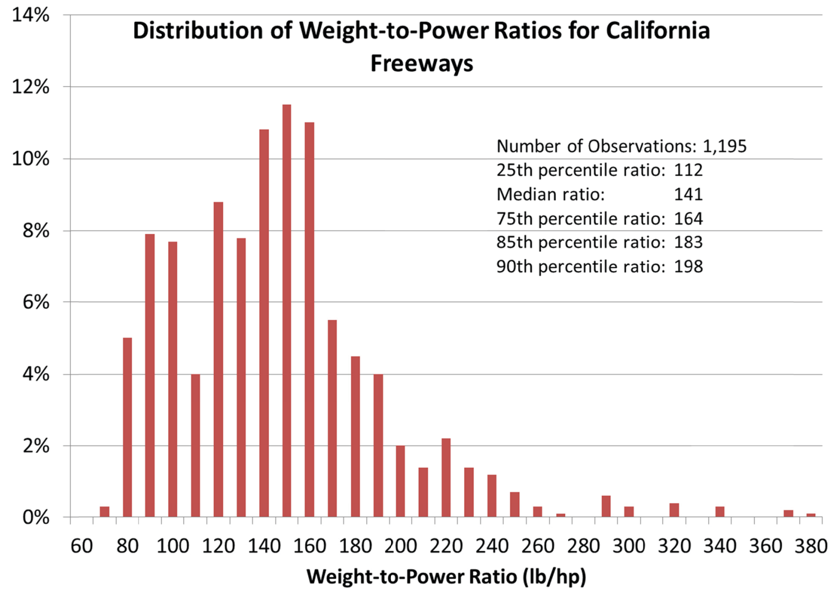
8.5 Calibration of Acceleration Profiles

Steps 2 and 3 in the analysis process were for developing the truck acceleration functions (relationships between the maximum acceleration and speed) that would be used in the microsimulation model—in this case, VISSIM. Step 2 focused on developing the functions themselves. Step 3 aimed to incorporate those functions into VISSIM and then to see what results were produced and whether any other VISSIM parameters needed to be adjusted to generate trajectories (predictions of speed versus distance) that were consistent with expectations from other research efforts. It seemed best to do these two steps simultaneously because there might be iterations, which proved to be true: two iterations were needed to reach closure.

8.5.1 Background on Truck Acceleration and Deceleration Profiles

In the HCM 2010, there are truck performance curves (Exhibit 11-21, HCM) for trucks with a weight/power ratio of 200 lb/hp. The reference data used to develop this truck performance

Exhibit 57. Weight-to-horsepower ratio distribution example.



Source: Adapted from Figure D-5: Distribution of Estimated Weight-to-Power Ratios for California Freeways, *NCHRP Report 505* (Harwood et al., 2003).

curve is found in the paper "Survey of Uphill Speeds of Trucks on Mountain Grades" (Willey, 1949). Trucks with weight/power ratios of about 200lb/hp were selected to develop the model since they would have acceptable operating characteristics from the standpoint of the highway users. However, applying a single truck performance curve for one weight/power ratio for all trucks reduces the accuracy of any analysis conducted.

To develop multiple truck performance curves for specific weight/power ratios, the following procedure can be followed:

- Find representative weight/power ratios according to the probability distributions of weight/power ratios. Figures D-5 through D-10 in *NCHRP Report 505: Review of Truck Characteristics as Factors in Roadway Designs* (Harwood et al., 2003) are distributions for several states. The figures also show the 25th-, 75th-, 85th-, and 90th-percentile ratios that could be used to get the specific values of weight/power ratios (see Exhibit 57).
- Apply specific values of the weight/power ratio to develop truck performance curves. Different weight/power ratios lead to different acceleration rates. Table 29 in Chapter 5 of *NCHRP Report 505* (reproduced in Exhibit 58) shows the acceleration rate with a given weight/power ratio and speed. The speed profile computations in Appendix E of *NCHRP Report 505* can be used to determine acceleration rates for different grades (Harwood et al., 2003).

Exhibit 58. Average truck acceleration capabilities.*

Weight-to-Power Ratio (lb/hp)	Acceleration rate (fpss)			
	0 mph	10 mph	20 mph	30 mph
100	1.87	1.70	1.47	1.29
200	1.22	1.08	0.96	0.79
300	0.91	0.81	0.72	0.58
400	0.71	0.61	0.50	0.36

*Average acceleration capabilities of trucks accelerating from specified speed to 64 km/hr (40 mph).
Source: *NCHRP Report 505* (Harwood et al., 2003).

8.5.2 Approach to Calibrating VISSIM Truck Profiles

Steps 2 and 3 started with a review of the literature on truck performance. The review showed that the procedure described in *NCHRP Report 505* (Harwood et al., 2003) would be a good starting point for developing a predictive model. The procedure described in the report could predict the performance of various truck types on specific grades or sequences of grades. Moreover, the procedure was codified in an Excel spreadsheet on a floppy disk that was included with the report. The spreadsheet produced speed-versus-distance trajectories based on user-specified inputs. (In the text that follows, this model is referred to as the "*NCHRP Report 505* spreadsheet.")

It was found that the *NCHRP Report 505* spreadsheet did produce the results presented in *NCHRP Report 505*—for example, if the weight-to-power ratio was set to 200 lb/hp and the weight-to-frontal-area ratio was set to 580 lb/ft^2, the graphs and tables shown in the report could be produced. (It is interesting, however, that this value for the weight-to-frontal-area ratio was different from the default value that the spreadsheet would have selected automatically.)

A check of the *NCHRP Report 505* spreadsheet's predictions with other sources suggested that it was likely to be a valid representation of truck performance. It could generate the acceleration and deceleration curves shown in the AASHTO Green Book. (We assume this is because the intent was to use the *NCHRP Report 505* findings in the AASHTO Green Book.) However, it could not generate the trajectories shown in the HCM. This is probably due to differences in assumptions about truck characteristics.

However, creation of the acceleration functions revealed a problem: a marked and abrupt decrease in acceleration arose at a speed of 10 ft/sec. The report and the logic called for different equations to be used to predict the tractive effort (acceleration produced by the engine) above and below this speed, but there was no indication that the acceleration value should change dramatically. It seemed to make more sense for the values to match where the logic changed (which we believe is what was intended). It seemed that a logic error was made in creating the program. Assuming this was the case, a change was to rectify this anomaly, and the trajectory predictions of the new code were compared with the old. The difference was very small.

With an expectation that the spreadsheet would now produce acceptable acceleration functions, Step 4 commenced. The acceleration functions were coded into VISSIM and simulations were conducted. However, the results did not match. VISSIM predicted significantly lower crawl speeds on the upgrades.

A check of VISSIM logic showed that it automatically adjusted the acceleration rates up or down by 1% of gravity for every 1% change in grade (decreasing it for upgrades and increasing it for downgrades). This is consistent with the effect that should arise from changes in grade.

A check of the *NCHRP Report 505* spreadsheet revealed three more problems, two major and one minor. The first was that the influence of grade was omitted even though its influence was described correctly in the report. A grade term did appear in the formula for predicting the tractive effort (inconsistent with the text of the report), but the influence of grade did not appear in the resistance equations. (Moreover, the way in which grade appeared in the tractive effort equation did not make logical sense.) The second problem was that there was no upper bound on the tractive effort due to the weight on the powered axles and/or the friction between the tire and the road. The third was that the coefficient for the V' term in the resistance equation used a value of 0.0004, while the report showed 0.004. Using 0.004 in the spreadsheet produced illogical results, so it was concluded that the value shown in the text was a typographical error.

In light of these findings, it was necessary to make two significant changes to the *NCHRP Report 505* spreadsheet. First, the effect of grade was introduced in the resistance equations; second, a limit on the tractive effort was added based on the percentage of truck weight on the powered axles and the coefficient of friction.

After making these changes, the new model's predictions were compared with those from a model developed by Rakha et al. (2001). Rakha et al.'s model differed in subtle ways from that contained in the revised *NCHRP Report 505* spreadsheet, but it seemed like the two models should produce similar results. To check its logic, Rakha et al.'s model was codified in an adaptation of the *NCHRP Report 505* spreadsheet. The finding was that not only was the code capable of producing the results shown in Rakha et al., but its parameter values could also be adjusted to produce the results predicted by the revised *NCHRP Report 505* spreadsheet and vice versa. Hence, it was concluded that the modified *NCHRP Report 505* spreadsheet was producing defensible results.

A return to Step 3 now showed that the truck trajectories (speeds versus distance) predicted by the revised *NCHRP Report 505* spreadsheet agreed with the predictions from VISSIM. This was true across the entire range of grades and weight-to-horsepower ratios.

8.6 Truck Footprint for VISSIM

A side effort involved creating VISSIM footprints (i.e., lengths, widths) of the Class 5 and 9 trucks. The effect of these footprints was two-fold in the main simulations. First, the footprints affected the length of the trucks in the car-following and lane-changing behavior. Second, from a display standpoint, the footprints determined the appearance of trucks in the animations.

8.7 VISSIM Simulations and PCE and Speed Model Development

Steps 4 and 5 were focused on conducting the VISSIM simulations and developing the predictive models for PCEs and truck speeds. At first, the expectation was that these steps would be done in series. However, as was the case with Steps 2 and 3, the results from the VISSIM simulations suggested useful ways to think about the predictive equations, so the two steps were done in parallel.

About 6,552 combinations of truck mix, grade, and traffic flow rate were simulated. The parameters that defined each simulation were as follows:

- FHWA Class 5 (single-unit trucks) and 9 (semitrailer trucks);
- Weight-to-horsepower ratios of 50, 100, 150, and 200 lbs/hp;
- Grades from –6% to 6% (13 grades total);
- Truck percentages of 0%, 10%, 20%, 30%, 40%, 50% and 100%; and
- Flow rates of 240, 600, 1200, 1800, 1920, 2040, 2160, 2280, and 2400 vehicles per hour per lane (veh/hr/lane).

The flow rates are equivalent to V/C ratios of 10%, 25%, 50%, 75%, 80%, 85%, 90%, 95%, and 100% for the all-automobile (no truck) condition.

Rather than work with each simulation separately, scenarios were formed in which the nine V/C conditions associated with each combination of FHWA class, weight-to-power ratio, grade, and truck percentage were grouped together. This resulted in 637 scenarios: 520 mixed scenarios (2*4*5*13) and 13 all-automobile scenarios plus 104 all-truck scenarios (2*4*13). The methodology was developed based on the simulation results from these scenarios.

8.8 The Speed Prediction Models

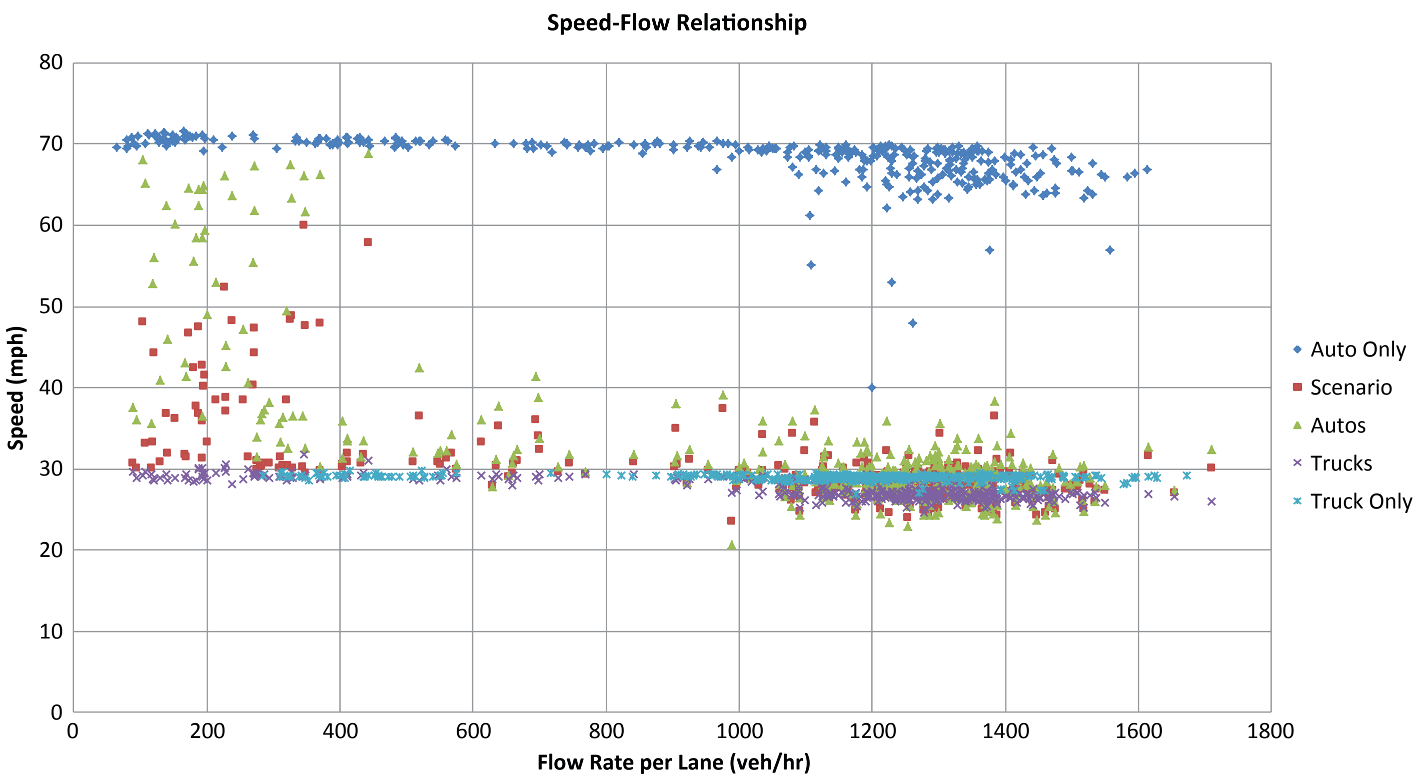
The steps in the procedure that focus on predicting the truck speed are motivated by Exhibit 59. It shows the speed-flow plot for this same condition. In fact, the plot also shows the speed-flow relationships for the truck and automobile speeds separately (in the 30% trucks case) as well as two other cases: automobiles-only and trucks-only.

The data points marked "Scenario" are the average mixed speeds for the 30% truck condition. At low flow, they are scattered between 40–70 mph, but they quickly drop to around 30 mph (the truck crawl speed) as the flow rate increases. The automobile speeds, marked "Autos," follow a similar trend (as they should since 70% of the traffic stream is automobiles). This motivates a prediction model that allows the values to drop from the all-automobile condition to the all-truck condition. This is a new idea in the context of the HCM procedures. The trucks speeds, marked "Trucks," are all at the crawl speed for the 6% grade, as they should be given the length of the segment (5 miles).

The data points marked "Auto Only" are for an all-automobile condition. To make the V/C ratios match, the automobile-only flow rates can be downward adjusted so that the automobile-only maximum flow rate matches that of the mixed scenario. The automobile-only speeds stay at or near 70 mph until capacity is reached.

The data points marked "truck only" are from the simulation of a traffic stream involving 100% trucks. To make the V/C values match in this instance, the flow rates have been upward adjusted so that the actual maximum flow rate in the all-truck circumstance (855 veh/hr/lane) maps to the maximum flow rate in the case under study (again, 1,500 veh/hr/lane).

Exhibit 59. Truck and automobile speed-flow relationships on a +6% grade.



Predicting the truck speeds proved to be relatively simple. In all 636 scenarios involving trucks (including the 100% truck case), the truck speed proved to match that which is derivable from the acceleration function, the deceleration function, and the length of the grade:

$$s_t = \frac{L}{t(L|g, s_o, \omega)} \qquad \text{Equation 27}$$

where

s_t = truck speed (mi/hr);
L = length of segment with grade; and
$t(L|g,s_0,\omega)$ = the time required to travel the distance, L, given the grade involved, g, the truck's initial speed upon entering the segment, s_0, and the truck's acceleration capabilities, ω.

The specific equations employed in simulating the movement of the truck through time are adapted from Appendix E of *NCHRP Report 505* (Harwood et al., 2003):

- **Computation of total resistance:**

  If $v > 10$ ft/sec then:

$$Rr = -0.2445 - 0.0004v - \frac{222.6 * \beta_{ele}}{WtHp * v} \qquad \text{Equation 28}$$

  If $v \le 10$ ft/sec then:

$$Rr = -0.2445 - 0.0004v \qquad \text{Equation 29}$$

$$Ra = -0.021 * \alpha_{ele} * v^2 / WtFa \qquad \text{Equation 30}$$

$$Rg = -32.17 * g \qquad \text{Equation 31}$$

$$R = Rr + Ra + Rg \qquad \text{Equation 32}$$

- **Computation of tractive effort:**

$$TE_{ENG} = \frac{15368 * \beta_{ele}}{WtHp * Max(10, v) + 14080 / Max(10.v)} \qquad \text{Equation 33}$$

$$TE_{ADH} = 32.2 * \mu * \rho * (1 - ABS(g)) \qquad \text{Equation 34}$$

$$TE = Min(TE_{ENG}, TE_{ADH}) \qquad \text{Equation 35}$$

- **Computation of vehicle position (*d*), velocity (*v*), and acceleration (*a*) at time *t*:**

$$a(t) = TE + R \qquad \text{Equation 36}$$

$$v(t) = \int v_0 + a(t)dt \qquad \text{Equation 37}$$

$$d(t) = \int d_0 + v(t)dt \qquad \text{Equation 38}$$

  where

  v = the speed at a given point in time (ft/sec);
  g = the grade (as a decimal);
  $WtHp$ = the weight-to-horsepower ratio (lb/Hp);

$WtFa$ = the weight-to-frontal-area ratio (lb/ft^2);
α_{ele} = an altitude-related adjustment factor for air resistance for converting sea-level aerodynamic drag to local elevation is equal to $(1 - 0.000006887 * \text{ft. elevation})^{4.255}$;
β_{ele} = an altitude-related adjustment factor for rolling resistance;
μ = the coefficient of friction between the tire and the road;
ρ = the percentage of the truck's weight on the powered axles;
Rr = the acceleration due rolling resistance (ft/sec^2);
Ra = the acceleration due to air resistance (ft/sec^2);
Rg = the acceleration due to grade-related resistance (ft/sec^2);
R = the total acceleration due to resistance (ft/sec^2);
TE_{ENG} = the tractive effort acceleration provided by the engine (ft/sec^2);
TE_{ADH} = the tractive effort acceleration that can actually be applied given the limitation imposed by μ and ρ (ft/sec^2);
TE = the actual tractive effort applied expressed as acceleration (ft/sec^2);
$a(t)$ = the acceleration at any given point in time (ft/sec^2);
$v(t)$ = the velocity at any given point in time (ft/sec);
$d(t)$ = the distance the truck has gone (ft.); and
dt = the increment of time (e.g., 1 second) being used in the simulation.

8.8.1 Predicting Automobile Speeds

An interesting and important finding is that automobile speed is affected by the trucks, especially when the truck percentage is high and the grade is steep. Hence, for high truck percentages, the automobile speeds need to be estimated as well as the truck speeds. The reason is that when the truck percentage is high and the grades are steep, the automobiles cannot easily overtake the trucks. The automobiles are constrained and in the limit have a speed that converges to the truck speed—that is to say, they become entirely (or effectively) constrained by the truck performance. Exhibit 10 illustrates this in the case of 30% trucks on a 6% upgrade.

A method was developed to predict the automobile speed as a function of the scenario conditions. Examination of the individual scenario runs suggested the following trends:

- The automobile speed is always high when the V/C ratio is low. Often, the speed at zero flow is the auto-only free-flow speed, but not always.
- When the truck percentage is low as on downgrades and on the level, the automobiles are able to follow a speed curve that closely matches the all-automobile condition.
- When the truck percentage is high and on upgrades, the automobile speeds decline to the truck speed as the V/C ratio increases.
- The pattern of decrease follows that of a logistics curve (as is commonly used in logit models). As the V/C ratio increases, the automobile speeds decline slowly at first, then more rapidly, and then more slowly as the truck speed is reached. Hence, the automobile speed asymptotically approaches limiting speeds for both low and high V/C ratios. This pattern can be seen in Exhibit 10.
- There is variation in the range of V/C ratios (or flow rates) over which this decline occurs. It is a wide range (say from V/C = 0.1 to V/C = 0.9) when the grade is slight, the truck percentage is low, and the weight-to-horsepower ratio is low (e.g., a 2% grade, 10% trucks, and a truck with only 50 lb/hp. It is narrow (say, from V/C = 0.1 to V/C = 0.2) when the grade is steep, the truck percentage is high, and the weight-to-horsepower ratio is high (e.g., a 6% grade, 30% trucks, and a truck with 200 lb/hp). Exhibit 59 shows the condition for a 6% grade, 30% trucks, and 150 lb/hp.

A simple logistics function is used to predict these automobile speed trends:

$$s_a = s_{to} + (s_{ao} - s_{to})\left(\frac{e^{-\beta\frac{v-v_m}{\Delta V}}}{1+e^{-\beta\frac{v-v_m}{\Delta V}}}\right) \quad \text{Equation 39}$$

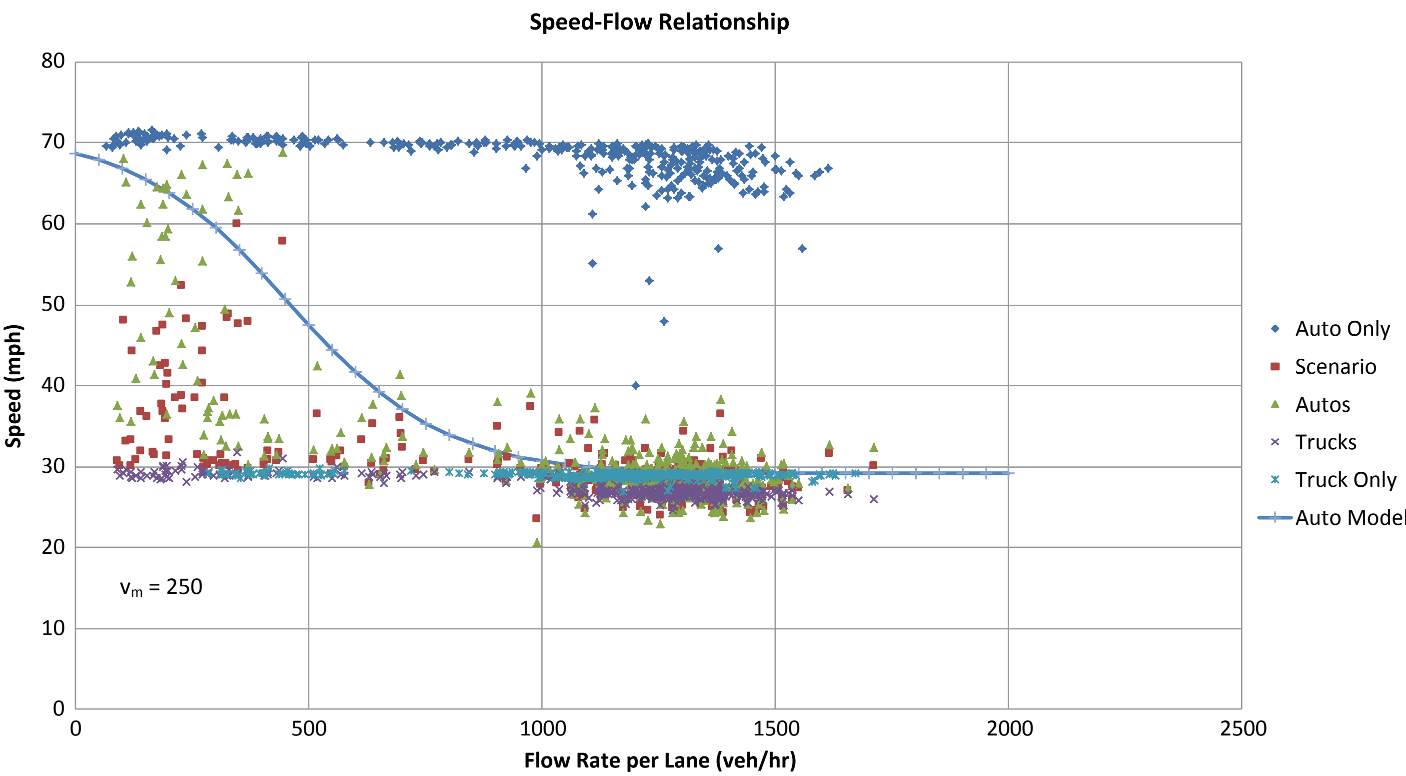
where

s_a = the automobile speed at flow rate v;
s_{ao} = the automobile-only speed that would arise at flow rate v (taking into account the PCE value);
s_{to} = the truck-only speed that would arise at flow rate v (again taking into account the PCE values for the mixed flow case and the all-truck case);
v_m = the flow rate at which the automobile speed has accomplished half of its transition from s_{ao} to s_{to},
ΔV = the range of flow rates over which the transition occurs; and
β = a calibration coefficient that ensures the following holds true:

$$-\beta\frac{v_m - \frac{\Delta V}{2}}{\Delta V} = 5 \quad \textit{and} \quad -\beta\frac{v_m + \frac{\Delta V}{2}}{\Delta V} = -5 \quad \text{Equation 40}$$

This ensures that the logit term within the large parentheses is approximately equal to 1 when $v = v_m - \Delta V/2$ and equal to 0 when $v = v_m + \Delta V/2$. In Exhibit 60, v_m is approximately 250 veh/hr/lane and ΔV is about 500 (from 100 to 600).

Exhibit 60. A model for estimating the automobile speed relationships on a +6% grade.



Note: +6% grade for a mixed traffic stream involving 30% Class 9 Trucks with 150 lbs/hp.

Exhibit 60 shows the automobile speed function that has been fitted to the automobile speed trends in the exhibit. The smooth line represents the automobile speed estimated by Equation 39 and appropriate values of v_m, ΔV, and β.

A two-step process was involved in developing a procedure to create equations that would estimate v_m, ΔV, and β for a given situation. First, for each of the 520 scenarios, estimates of v_m and ΔV were obtained through statistical analysis. Then, the resulting estimates were placed in a database and curve-fitting techniques were used to develop estimates of the three parameters.

Predicting v_m proved to be most challenging. The logic shown in Exhibit 61 works well.

Clearly, this is not the end result of a formal regression analysis; rather, it is derived from careful examination of the trends exhibited in v_m in response to changes in the other variables involved. Also, to some degree, it reflects the vagaries of the simulation environment.

It was clear from examining the initial results that for grades below 1% (the first seven conditions), the v_m value is high if the truck percentage is 30% or less and low if it is greater. It was also clear that for grades of 1% or greater, the v_m value is highest when the percent trucks is lowest and it declines as the percent trucks increases and that it falls sharply in response to increases in the weight-to-horsepower ratio. This logic is reflected in the "if–then" logic presented above, including the equation that predicts v_m for grades of 1% and greater.

A more detailed examination of the trends for grades of 1% or more revealed:

- The patterns of predicted and observed v_m clearly matched, especially for steeper grades.
- For the less-steep grades, it was also clear that the stochasticity in the simulation process makes the trends less deterministic in appearance. Thus, the strength in the model presented in the "if–then" logic is that it converges to the simulation results observed as the grades increase in severity, which is a very good property for the model to have.

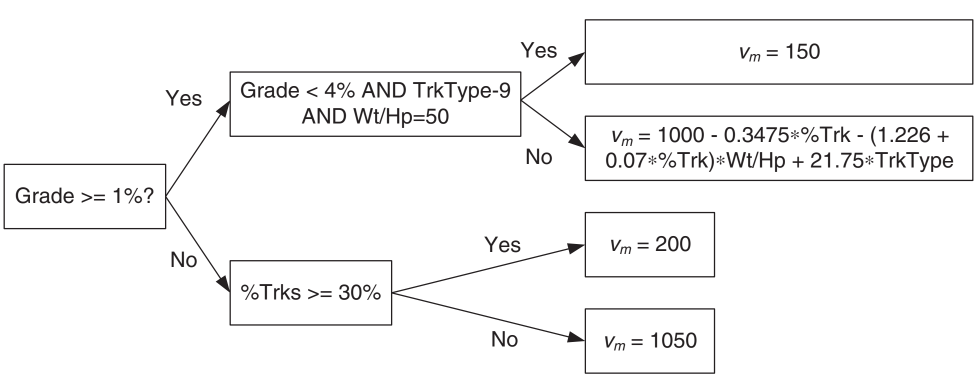
The estimation of values for ΔV and β is far more straightforward. In this instance, a slight variation of Equation 39 is used:

$$s_a = s_{to} + (s_{ao} - s_{to})\left(\frac{e^{\frac{v - v_m}{\theta}}}{1 + e^{\frac{v - v_m}{\theta}}}\right) \qquad \text{Equation 41}$$

where θ reflects the combined effects of ΔV and β. The result is

$$\theta = \underset{32.68}{0.2510} * v_m \quad R^2 = 0.7964 \qquad \text{Equation 42}$$

Exhibit 61. Logic for determining v_m values.



The *t* statistic, shown below the coefficient for v_m, being significantly greater than 1.97, demonstrates that the effect is statistically significant.

In summary, the prediction procedure for truck speed is relatively simple. Moreover, it predicts defensible results not only for the density that will arise in a given situation, but both truck and car speeds. The procedure works whether the truck flows are of a single type or mixed. It is known to work for grades from –6% to +6% and for truck percentages up to 50%.

8.9 Freeway Truck and Automobile Speed Model Case Study

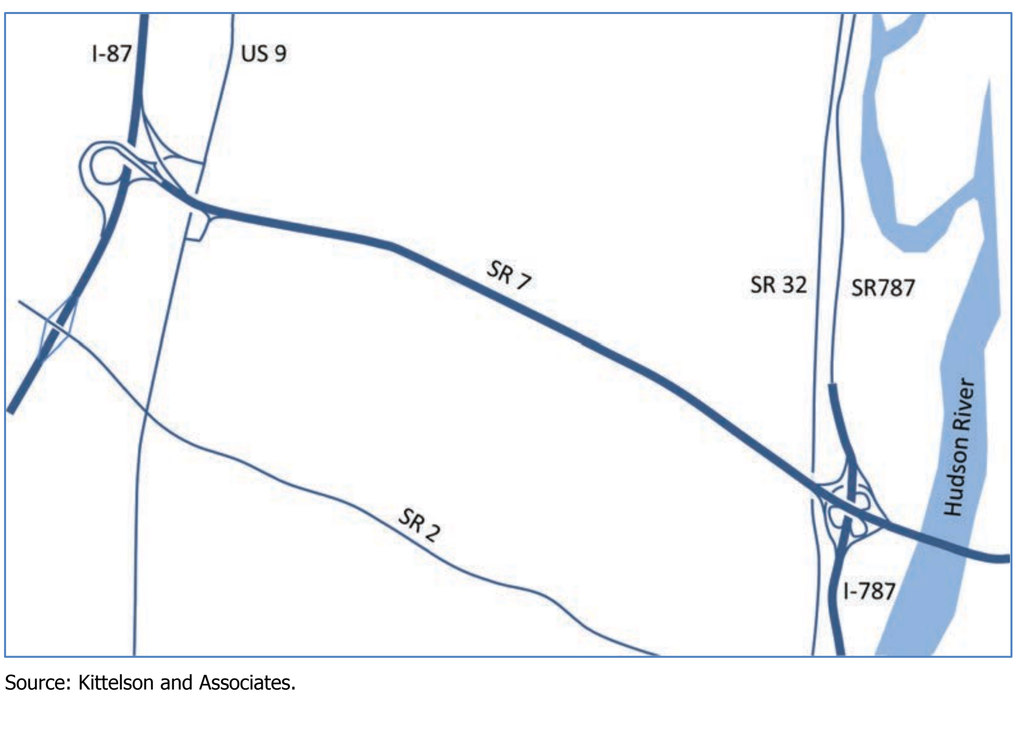
To test the new procedures, a case study was conducted. To generate "field data" for the case study, a VISSIM simulation model of the study section was created based on data provided by New York State (NYS) DOT.

The selected real-world case study site was a 3.5-mile section of New York State Route 7 just north of Albany (see Exhibit 62). This same site was used in the *Highway Capacity Manual Applications Guidebook* (Kittelson et al., 2003). A VISSIM model (PTV Group, n.d.) was developed and calibrated for the case study site to generate the "observed" data against which the case study results could be compared.

The facility is a freeway running between I-87 on the west to I-787 on the east. The percentage of trucks is about 6%. The free-flow speed is 55 mph. The test facility has the following grades:

- Westbound:
  - +1.92% for 3,769 ft.;
  - +4.80% for 1,854 ft.;
  - +1.00% for 4,839 ft.;
  - +4.00% for 1,919 ft.;

Exhibit 62. New York State Route 7 freeway test site.



Source: Kittelson and Associates.

  - –0.80% for 1,192 ft.; and
  - –2.10% for 5,299 ft.
- Eastbound: opposite grades for same lengths.

A vertical profile of the facility is shown in Exhibit 63.

The facility has two lanes eastbound and three westbound. The third westbound lane was originally intended to be a truck climbing lane, but today it is used for all traffic. The A.M. traffic is heavier eastbound; the P.M. traffic is heavier westbound. Eastbound, vehicles enter the study section at about 40–50 mph, accelerate, and then continue eastward to the I-787 interchange. Westbound, vehicles enter at 30–50 mph coming either from the bridge across the Hudson River or one of the two I-787 ramps. Of the two ramps, the loop ramp (northbound to westbound) has the most traffic; the right-hand ramp (southbound to westbound) has very little traffic. Typically, there are no queues in either direction in the A.M. peak, but in the P.M. peak, there is often a queue westbound that extends half the length of the facility. Most of the westbound traffic wants to exit via the single-lane right-hand ramp at the western end; traffic from about 2.5 lanes is converging on a single-lane exit.

The facility is instrumented with speed traps about at the midpoint and video cameras at either end. Data from the speed traps is not archived. However, NYSDOT periodically does short counts including truck classifications.

The A.M. and P.M. peaks for the existing conditions were studied for the test site as well as hypothetical P.M. peaks that involved 15% and 30% trucks as well as a change to the geometry at the western end so that a bottleneck would not be created. (The two-lane exit eliminates the queuing problem.) The higher truck percentages are of interest because of the new methodology. A summary of the simulated and observed network performance for these conditions is shown in Exhibit 64. The data for the real-world A.M. and P.M. peak conditions are shown in the first four columns. The performance for the hypothetical situations involving 15% and 30% trucks are shown in the right-hand four columns.

The simulation model produces results consistent with observed performance. Most importantly, it predicts a westbound queue in the P.M. peak that extends about half-way back to the I-787 interchange. This queuing condition is very common.

The proposed analysis procedure (labeled "New HCM Model" in Exhibit 65) was applied, and its predictions were compared with the performance predictions provided by the VISSIM simulation model. Both directions were studied in detail, but the main focus in this report is on the westbound direction because it has the significant upgrades. The LOS predictions westbound were checked at the end of each section. The location reported here for the eastbound direction is at the end of the 2.1% grade.

Exhibit 63. Vertical profile of the NY State Route 7 freeway test site.

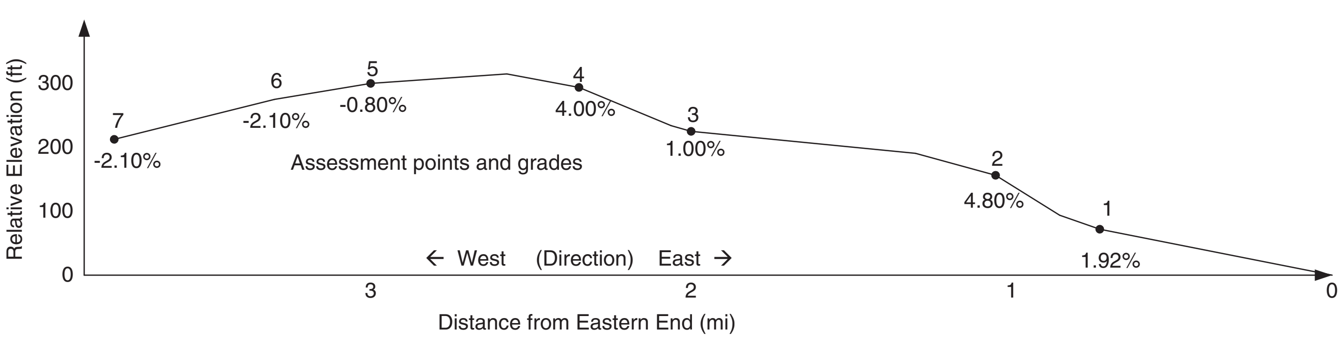


Exhibit 64. Simulated actual and hypothetical results for higher truck percentages for NY State Route 7 site.

	Base Case				15% Trucks		30% Trucks	
	AM Peak		PM Peak		PM Peak		PM Peak	
Data Item	East	West	East	West	East	West	East	West
Overall Flow Rate (vph)	2902	2228	2354	2972	2354	3024	2354	3024
Peak Hour Factor	0.83	0.81	0.89	0.92	0.89	0.92	0.89	0.92
Truck Percentages	9.18%	5.64%	6.59%	5.14%	15.00%	15.00%	30.00%	30.00%
Class 4	0.93%	0.56%	0.94%	0.71%	1.53%	1.49%	4.29%	4.13%
Class 5	3.91%	2.47%	2.35%	2.36%	6.39%	6.57%	10.71%	13.76%
Class 6	1.02%	0.56%	0.71%	0.38%	1.67%	1.49%	3.21%	2.20%
Class 7	0.25%	0.14%	0.14%	0.09%	0.42%	0.37%	0.64%	0.55%
Class 8	0.93%	0.70%	1.51%	0.66%	1.53%	1.86%	6.86%	3.85%
Class 9	1.70%	0.93%	0.52%	0.75%	2.78%	2.48%	2.36%	4.40%
Class 10	0.42%	0.19%	0.24%	0.14%	0.69%	0.50%	1.07%	0.83%
Class 11	0.00%	0.05%	0.05%	0.00%	0.00%	0.12%	0.21%	0.00%
Class 12	0.00%	0.00%	0.05%	0.00%	0.00%	0.00%	0.21%	0.00%
Class 13	0.00%	0.05%	0.09%	0.05%	0.00%	0.12%	0.43%	0.28%
Vehicle-Miles (8 hrs)								
Autos	34965	55077	24659	73508	22725	68107	19266	56370
Trucks	4397	3291	2455	4124	5332	11809	10917	23391
All	39362	58369	27115	77632	28057	79915	30183	79761
Vehicle-Hours (8 hrs)								
Autos	499	812	350	3853	323	1037	274	986
Trucks	64	51	35	232	77	182	157	408
All	563	864	386	4085	400	1220	432	1395
Avg Speed (mph)								
Autos	70.1	67.8	70.4	19.1	70.3	65.7	70.3	57.2
Trucks	68.5	64.2	69.3	17.8	69.3	64.7	69.5	57.3
All	69.9	67.6	70.3	19.0	70.1	65.5	69.9	57.2

As can be seen from Exhibit 65, the proposed analysis procedure ("New HCM") predicts automobile and truck speeds that are generally consistent (within 6%) with those from the VISSIM model.

8.10 Freeway Truck Travel Time Reliability

Existing truck travel time reliability for one or more selected segments of a freeway can be obtained from the National Performance Management Research Data Set (NPMRDS) for the National Highway System (NHS) (FHWA, 2013, June 26). Resources did not permit the development of a model for predicting truck travel time reliability. However, the SHRP2-L08 methodology (Kittelson and Vandehey, 2012) can be used to estimate mixed flow travel time reliability. Until such time as better methods become available, the SHRP2-L08 results might be used as a proxy for truck travel time reliability (Kittelson, 2012).

8.10.1 Data on Existing Truck Reliability—NPMRDS

NPMRDS contains archived data on truck travel times by highway segment on the NHS, by 5-min-long time periods of the day. It is a vehicle-probe based data set. Separate travel times are reported for FHWA Vehicle Classes 7 and 8 (labeled "trucks" in the database); all other vehicle

Exhibit 65. New HCM procedure versus simulation model results for NY State Route 7 case study network.

Data Item		Westbound Assessment Location							EBD
	Segment Length (ft)	3769	1854	4839	1919	1192	2405	3894	4510
	Grade (%)	1.92%	4.80%	1.00%	4.00%	-0.80%	-2.1%(6)	-2.1%(7)	2.10%
PM Actual Conditions									
Observed Performance									
	Flow Rate (vphpl)	991	991	991	991	991	991	1486	1177
	Auto Speed (mph)	70	68	70	68	70	70	70	70
	Truck Speed (mph)	67	62	68	64	66	70	66	68
	Density (veh/mi/ln)	14	16	17	17	17	17	10	8
New HCM Model									
	PCE	1.52	1.89	1.40	1.79	1.16	1.00	1.00	1.54
	Auto Speed (mph)	68.4	66.0	70.0	68.2	70.0	70.0	66.5	67.4
	Truck Speed (mph)	65.7	59.5	69.9	65.3	69.9	69.9	65.6	65.3
	Density (veh/mi/ln)	13.2	13.7	14.4	13.2	12.9	12.9	21.1	16.3
PM 15% Trucks									
Observed Performance									
	Flow Rate (vphpl)								
	Auto Speed (mph)	69.3	68.5	69.1	68.6	68.8	69.1	69.2	69.4
	Truck Speed (mph)	67.7	62.1	67.8	63.8	65.5	69.4	66.7	67.1
	Density (veh/mi/ln)	16.3	16.6	16.3	16.5	16.4	16.2	7.5	6.9
New HCM Model									
	PCE	1.52	1.89	1.40	1.79	1.16	1.00	1.00	1.54
	Auto Speed (mph)	68.3	65.3	69.9	67.9	70.0	70.0	66.5	67.0
	Truck Speed (mph)	65.6	59.2	69.8	65.0	69.9	69.9	65.6	64.8
	Density (veh/mi/ln)	13.3	14.0	12.9	13.3	12.9	12.9	21.1	16.5
PM 30% Trucks									
Observed Performance									
	Flow Rate (vphpl)								
	Auto Speed (mph)	69.1	67.8	68.9	67.8	66.2	62.3	68.9	69.3
	Truck Speed (mph)	67.4	61.5	67.5	63.1	63.0	62.1	66.0	66.9
	Density (veh/mi/ln)	16.4	17.0	16.4	16.9	17.6	21.3	7.4	7.8
New HCM Model									
	PCE	1.52	1.89	1.40	1.79	1.16	1.00	1.00	1.54
	Auto Speed (mph)	68.0	63.7	69.8	67.1	69.8	69.9	65.6	66.1
	Truck Speed (mph)	65.2	58.1	69.6	64.2	69.8	69.9	65.6	63.8
	Density (veh/mi/ln)	13.4	14.5	12.9	13.6	12.9	12.9	21.4	16.8

classes (labeled "passenger vehicles"); and all vehicles combined. The number of vehicles and the percent of trucks in the data are not reported.

Historic data is available for the Interstate freeway system back to October 2011. For all other highways on the NHS, data is available back to July 2013. A moderate amount of GIS database processing is required to make effective use of the data once downloaded.

8.10.2 Predicting Truck Reliability on Freeways

The SHRP2-L08 methodology can be used to predict mixed flow travel time reliability for a freeway facility. It is sensitive to recurring peak-period demands, day-to-day demand variability, the frequency and severity of bad weather, crash frequency, and the scheduling of work zones on the freeway facility. The methodology can be used to predict various travel time indices (TTIs), of which, the 50th-percentile and the 95th-percentile TTIs are required.

The median (50th-) and 95th-percentile TTIs predicted using the SHRP2-L08 method are entered into the following two equations, which are solved for the values of the parameters *k* and *c*:

$$TTI(50\%) = \sqrt[c]{(2)^{1/k} - 1} \qquad \text{Equation 43}$$

$$TTI(95\%) = \sqrt[c]{(20)^{1/k} - 1} \qquad \text{Equation 44}$$

The agency's target TTI threshold for on-time arrival (1.33 is recommended for freeways) is then entered into the following Burr distribution equation (along with the previously determined values of *k* and *c*) to obtain the probability *P* of on-time arrival for mixed flow traffic on the facility:

$$P_{(TTI=1.33)} = 1 - (1 + TTI^{c})^{-k} \qquad \text{Equation 45}$$

Until a better method becomes available, the mixed flow traffic reliability (probability of on-time arrival) is assumed to be the same as for trucks.

If the analyst wishes a more precise forecast, the analyst might use the SHRP2-L08 method to predict existing reliability conditions and compare that estimate with the value obtained from the NPMRDS. The ratio of the observed truck value to the estimated mixed flow value might then be used to adjust the forecasted mixed flow reliability to obtain a calibrated prediction of truck travel time reliability. However, this approach has not been tested or validated in this research.

SECTION 9

Prediction of Arterial Truck Speeds

This section presents the recommended methodology for estimating truck speeds on arterial segments in between signalized intersections.

9.1 Existing Truck Treatment on Arterials in the HCM

Arterial analyses in the HCM (including signalized intersections, stop-controlled intersections, and roundabouts) use heavy-vehicle PCE values to adjust the saturation flow rates. Unlike the freeway methods, truck PCEs are not used to adjust the vehicle flow rates.

At the intersections, the saturation flow rate is adjusted by a heavy-vehicle adjustment factor, f_{HV}, as illustrated by this equation from "Chapter 18: Signalized Arterials," in the HCM:

$$s = s_0 f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lbp} f \qquad \text{Equation 46}$$

where

s = the adjusted saturation flow rate,
s_0 = the saturation flow rate under ideal conditions,
f_{HV} = the heavy-vehicle adjustment factor, and
all other $f_{..}$ values = other adjustment factors.

This same type of adjustment is used in stop-controlled intersections and roundabouts.

As with the freeway analysis methods, the heavy-vehicle adjustment factor f_{HV} is given by

$$f_{HV} = \frac{100}{100 + P_{HV}(E_T - 1)} \qquad \text{Equation 47}$$

where

P_{HV} = the percentage of heavy vehicles and
E_T = the PCE value; the PCE value for heavy vehicles is always 2.0.

The arterial is treated as a series of segments (see HCM, Chapters 16 and 17). Each segment begins and ends at a stopbar. A segment can have intermediate stop-controlled intersections and roundabouts, but no signalized intersections. A 10-step process is used to determine the "automobile LOS." Average speed is used to assess the LOS for the vehicular traffic stream in combination with the V/C ratio. The average speed also gives an indication of delay (and travel rate). Once the steps have been completed for each segment in the arterial, the overall metrics are determined through a distance-weighted average.

For each segment, the base free-flow speed is computed using HCM Equation 17-2:

$$S_{f0} = S_0 + f_{CS} + f_A \qquad \text{Equation 48}$$

where

S_{fo} = the base free-flow speed,
S_0 = a constant,
f_{CS} = an adjustment for cross section, and
f_A = an adjustment for the access points.

It would be possible to add an adjustment here for the truck mix, but this is not presently our first choice.

The base free-flow speed is then adjusted in HCM Equation 17-4 to account for intersection spacing through an additional adjustment factor f_L:

$$S_f = S_{f0} f_L \qquad \text{Equation 49}$$

A second equation (HCM Equation 17-3) is used to compute f_L. A subsequent equation (HCM Equation 17-5) provides an adjustment based on vehicle proximity (effectively density):

$$f_v = \frac{2}{1 + \left(1 - \frac{v_m}{52.8 * N_{th} S_f}\right)^{0.21}} \qquad \text{Equation 50}$$

where

f_v = the proximity adjustment factor,
v_m = the mid-segment demand flow rate,
N_{th} = the number of through lanes on the segment, and
S_f = the free-flow speed.

Exhibit 66 shows the effect of this mid-segment lane flow rate (veh/hr/lane) on the running speed. There is no discussion about trucks, so the assumption is that the relationships are for situations where the influence of heavy vehicles is negligible.

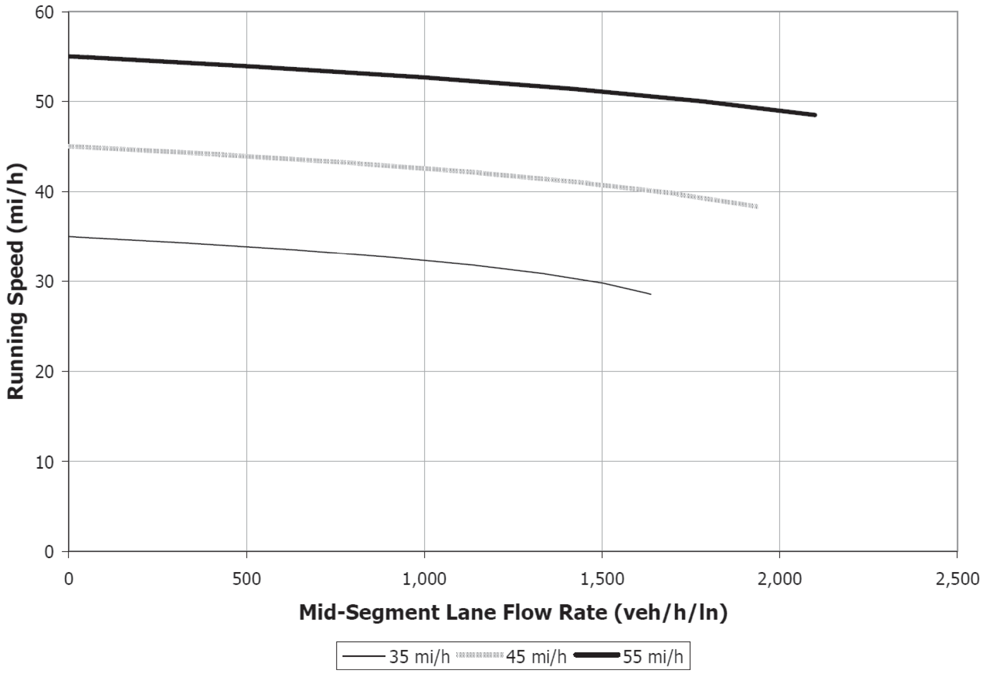
This effect of proximity is one of several adjustments that appear in HCM Equation 17-6 to compute the running time for the segment:

$$t_r = \frac{6.0 - l_1}{0.0025L} f_x + \frac{3600L}{5280S_f} f_v + \sum_{1=1}^{N_{ap}} d_{ap,i} + d_{other} \qquad \text{Equation 51}$$

where

t_r = the running time,
l_1 = the start-up lost time,
L = the segment length,
f_x = a control-type adjustment factor,
S_f = the free-flow speed,
f_v = the proximity adjustment factor,
$d_{ap,i}$ = the delay due to left and right turns from the street into access point intersection i,

Exhibit 66. Speed-flow relationship for urban street segments.



N_{ap} = the number of influential access point approaches along the segment, and
d_{other} = delay due to other sources along the segment.

For an overall arterial, the base free-flow speed is computed via

$$S_{fo,F} = \frac{\sum_{i=1}^{m} L_i}{\sum_{i=1}^{m} \frac{L_i}{S_{fo,i}}} \qquad \text{Equation 52}$$

where

$S_{fo,F}$ = the base free-flow speed for the facility,
L_i = the length of segment i,
m = the number of segments on the facility, and
$S_{fo,i}$ = the base free-flow speed for segment i.

The actual travel speed for the arterial is computed in a similar manner using

$$S_{T,F} = \frac{\sum_{i=1}^{m} L_i}{\sum_{i=1}^{m} \frac{L_i}{S_{T,seg,i}}} \qquad \text{Equation 53}$$

where

$S_{T,F}$ = the travel speed for the facility,
L_i = the length of segment i,
m = the number of segments on the facility, and
$S_{T,i}$ = the travel speed for segment i.

9.2 Approach

The new methodology captures the effects of trucks on arterial speeds in two places. The first is at the intersection where the through-delay and through-stop rate are determined for point facilities like signalized intersections. Here, new PCE values have been generated that adjust the saturation flow rate.

The second is at the midblock location between intersections, where the running time is determined for the section of the segment upstream of the control point (i.e., changes and/or adjustments). The intent in this latter case was to do this in a manner similar to that described previously for freeways.

Development of the new methodology was accomplished in six steps:

1. Develop acceleration profiles (acceleration versus speed, one for each truck type) that can be used as inputs to VISSIM. Compare the trajectory predictions (speed versus distance) of these profiles with those from prior studies. This is identical to the freeways.
2. Use a VISSIM model of a single-lane arterial with a constant grade to see if any VISSIM parameter values needed to be adjusted to generate speed-distance trajectories that were consistent with the findings from Step 1 above. This is identical to the freeways.
3. Conduct simulations of a wide range of truck types, weight-to-horsepower ratios, truck percentages, flow rates, and grades using a simulation model of an arterial segment that is two lanes wide with constant grades. Do this initially for one truck type (focused principally on FHWA Classes 5 and 9), and then for mixes of truck types and weight-to-horsepower ratios. This is similar to the freeways except a two-lane-wide arterial was employed.
4. Determine what predictive relationships can be used for truck PCEs and speeds based on the data from Step 3. This is similar to the procedure that was described for freeways.
5. Collect saturation flow rates for signalized intersections and see how these flow rates are affected by the truck mix. Prepare PCE values that can be used to properly adjust the saturation flow rates to those observed.
6. Test the resulting treatments for truck PCEs and speeds using a quasi-real case study whose setting is based on a real-world facility, but whose design and traffic mix details have been treated parametrically to allow tests of the effects of various other conditions (e.g., flow rates, truck mix percentages, and grades).

9.3 Acceleration Profiles

Steps 1 and 2 involved developing the truck acceleration functions (relationships between the maximum acceleration and speed) that would be used in VISSIM to model midblock arterial segment speeds. This work and the results obtained were the same as was the case for the freeway analysis.

9.4 Midblock Arterial Segment Speed Model Development

Steps 3 and 4 were focused on conducting the VISSIM simulations and developing the predictive models for midblock arterial truck speeds. At first, the expectation was that these steps would be done in series; however, as was the case with the freeway analysis, the results from the VISSIM simulations suggested useful ways to think about the predictive equations, so the two steps were done in parallel.

9.4.1 Test Site Selection

The investigation of the arterial segment midblock speed flow effects of trucks on extended grades was performed on a hypothetical arterial with no signals, consisting of 8 miles of level 6-lane street followed by 5 miles of 6-lane street with a grade. The grade on the 5-mile section varied from –6% to +6% in 1% increments (13 grades total). The hypothetical facility was simulated using the VISSIM microsimulation model (PTV Group, n.d.).

9.4.2 Simulation Model Application

About 6,552 combinations of truck mix, grade, and traffic flow rate were simulated, as was the case for the freeway analysis. The parameters for each combination were as follows:

- FHWA Class 5 and 9;
- Weight-to-horsepower ratios: 50, 100, 150, and 200 lbs/hp;
- Grades: –6% to 6% (13 grades total);
- Truck percentages: 0, 10%, 20%, 30%, 40%, 50% and 100%; and
- Flow rates: 180, 450, 900, 1350, 1440, 1530, 1620, 1710, and 1800 veh/hr/lane.

The flow rates were intended to be equivalent to V/C ratios of 10%, 25%, 50%, 75%, 80%, 85%, 90%, 95%, and 100% for the all-automobile condition.

As with the freeway analysis, *scenarios* were formed by grouping together the nine V/C conditions associated with each combination of FHWA class, weight-to-power ratio, grade, and truck percentage. This resulted in 637 scenarios: 520 mixed scenarios (2*4*5*13) plus 13 all-automobile scenarios plus 104 all-truck scenarios (2*4*13). The methodology was developed based on these scenarios.

9.5 The Predictive Procedure for Midblock Arterial Segment Speeds

The predictive procedure is very similar to the one created for freeways. It makes use of the same truck speed prediction model to create the predictions of truck speeds based on grades and segment lengths. It uses a set of equations to predict what the truck and automobile speeds will be.

One of the 637 scenarios can be used to illustrate the predictive procedure's main ideas.

Exhibit 67 shows a plot of 1-min flow-density data points for a mixed traffic stream on a 6% upgrade involving 30% Class 9 trucks at 150 lbs/hp. It also shows the flow-density relationship for an all-automobile traffic stream with a +6% grade.

It is immediately obvious, as was in the case of the freeway analysis, that the data points for the mixed traffic stream lie well below those for the all-automobile condition. Implicitly, the speeds are very different (the slopes of the relationships). Moreover, the maximum density achieved by the mixed flow is greater than that for the all-automobile flow.

In Exhibit 67, the graph shows an example flow-density relationship for an arterial segment that is two lanes wide on a +6% grade for both a mixed traffic stream involving 30% Class 9 Trucks with 150 lbs/hp and an all-automobile traffic stream.

Insofar as truck speeds are concerned, Exhibit 68 shows the speed-flow plot for this same condition. It also shows the speed-flow relationships for the truck and automobile speeds separately (in the 30% trucks case) as well as two other cases: automobiles only and trucks only.

Exhibit 67. Flow-density relationships for an arterial segment.

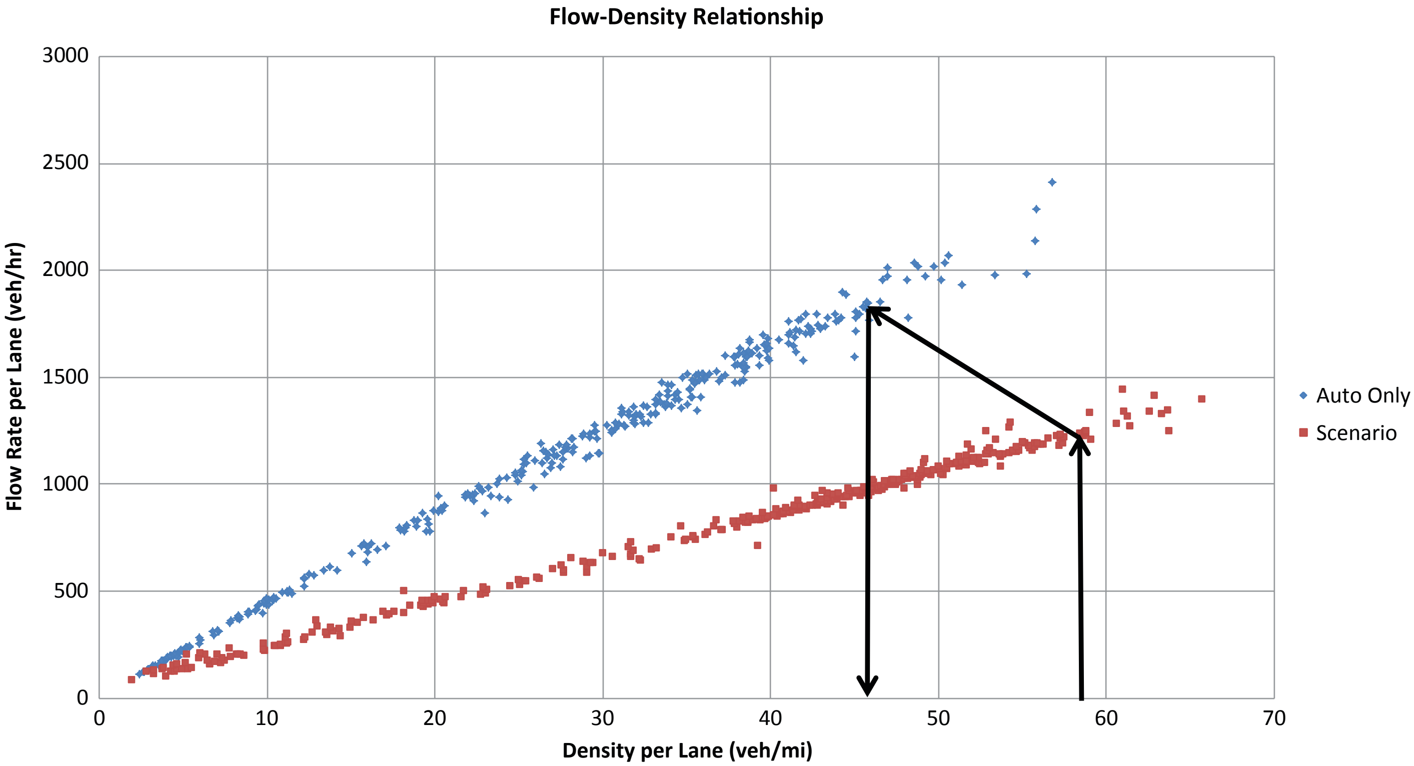
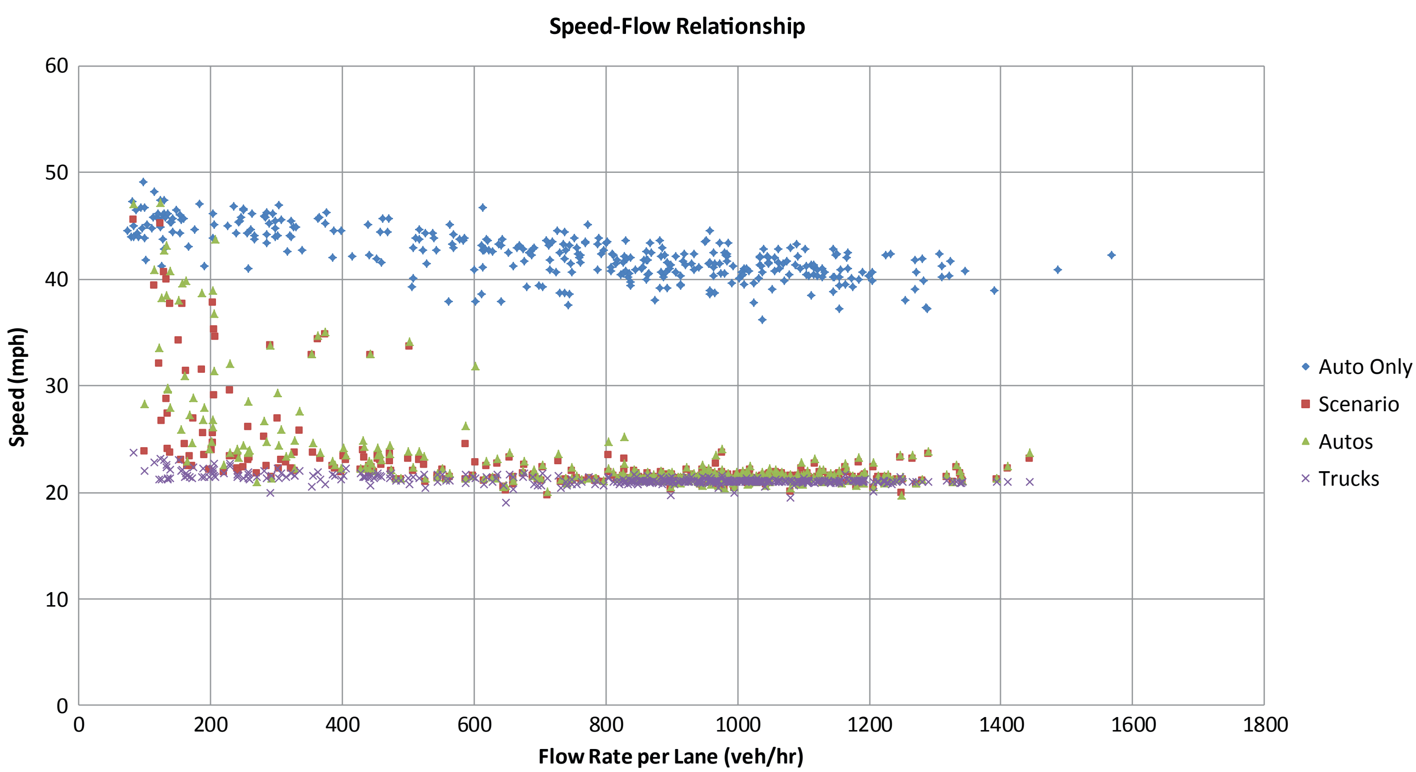


Exhibit 68. Speed-flow relationships on a +6% grade – 30% Class 9 trucks.



Note: for a +6% grade for both a mixed traffic stream involving 30% Class 9 trucks with 150 lbs/hp and an all-automobile traffic stream.

The data points marked "Scenario" are the average mixed speeds for the 30% truck condition. At low flow, they are scattered between 40–50 mph, but they quickly drop to around 20 mph (the truck crawl speed) as the flow rate increases. The automobile speeds, marked "Autos," follow a similar trend (as they should since 70% of the traffic stream is automobiles). This motivates a prediction model that allows the values to drop from the all-automobile condition to the all-truck condition. This is a new idea in the context of the HCM procedures. The trucks speeds, marked "Trucks," are all at the crawl speed for the 6% grade, as they should be given the length of the segment (5 miles).

The data points marked "Auto Only" are for an all-automobile condition. To make the V/C ratios match, the automobile-only flow rates are downward adjusted so that the automobile-only maximum flow rate matches that of the mixed scenario. This is effectively the reverse of the process described for Exhibit 67. The automobile-only speeds stay at or above 40 mph until capacity is reached.

The data points marked "truck only" are from a simulation of a traffic stream involving 100% trucks. To make the V/C values match in this instance, the flow rates are proportionally adjusted so that the actual maximum flow rate in the all-truck circumstance (855 veh/hr/lane) maps to the maximum flow rate in the case under study (again, 1500 veh/hr/lane).

9.5.1 Truck Speeds on Arterial Segments

Truck speeds (excluding intersection delays) are predicted in the same manner as they were for freeways. The truck speed is developed from the acceleration function, the deceleration function, and the length of the grade:

$$s_t = \frac{L}{t(L|g, s_o, \omega)}$$ Equation 54

where

L = the length of the grade segment and
$t(L|g, s_o, \omega)$ = the time required to travel the distance L given the grade involved, g, the truck's initial speed upon entering the segment, s_o, and the truck's acceleration capabilities ω.

As for the freeway analysis, the same specific equations are used to predict the movement of the truck through time (see Equations 28–38).

9.5.2 Automobile Speeds on Arterial Segments

Automobile speeds (excluding intersection delays) are predicted using a logistics equation, as was the case for freeways:

$$s_a = s_{to} + (s_{ao} - s_{to})\left(\frac{e^{-\beta\frac{v-v_m}{\Delta V}}}{1+e^{-\beta\frac{v-v_m}{\Delta V}}}\right)$$ Equation 55

where

s_a = the automobile speed at flow rate v,
s_{ao} = the automobile-only speed that would arise at flow rate v (taking into account the PCE value),

s_{to} = the truck-only speed that would arise at flow rate v (again taking into account the PCE values for the mixed flow case and the all-truck case),
v_m = the flow rate at which the automobile speed has accomplished half of its transition from s_{ao} to s_{to},
ΔV = the range of flow rates over which the transition occurs, and
β = a calibration coefficient that ensures the following holds true:

$$-\beta\frac{v_m-\frac{\Delta V}{2}}{\Delta V}=5 \quad \textit{and} \quad -\beta\frac{v_m+\frac{\Delta V}{2}}{\Delta V}=-5 \qquad \text{Equation 56}$$

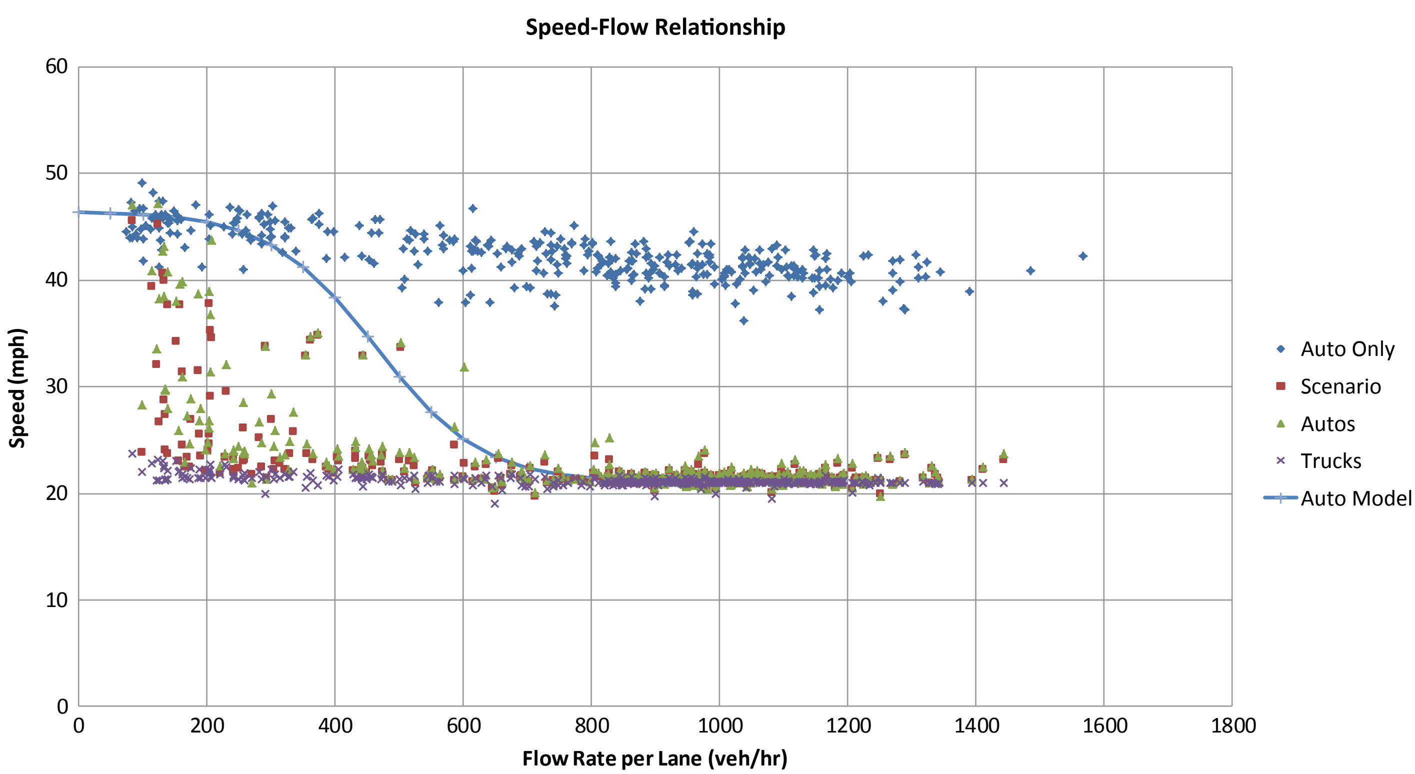
This ensures that the logit term within the large parentheses is approximately equal to 1 when $v = v_m - \Delta V/2$ and equal to 0 when $v = v_m + \Delta V/2$.

Exhibit 69 shows the automobile speed function that was fitted to the automobile speeds in Exhibit 68. The smooth line represents the automobile speed estimated by Equation 4 and appropriate values of v_m, ΔV, and β.

Exhibit 69 shows the estimated automobile speed relationship for arterials using the speed-flow relationships on a +6% grade for a mixed traffic stream involving 30% Class 9 trucks with 150 lbs/hp.

As with the freeway analysis, a two-step process was involved in developing a procedure to create equations that would estimate v_m, ΔV, and β for a given situation. First, for each of the 520 scenarios, estimates of v_m and ΔV were obtained through statistical analysis. Then, the resulting estimates were placed in a database and curve-fitting techniques were used to develop estimates of the three parameters. Predicting v_m proved to be most challenging. The following logic proved to be useful:

Exhibit 69. Example automobile speed relationship for arterials.



If (%Grade>=1%),

then v_m = 920 – 0.3475 * %Trk – (2.5 + 0.008 * %Trk * %Grade) * Wt/Hp + 20 * TrkType,

else v_m = 800.

Clearly, this is not the result of a formal regression analysis; rather, it is derived from careful examination of the trends exhibited in v_m in response to changes in the other variables involved.

From a review of the results it was clear that for grades below 1% (the first seven conditions), the v_m value is high if the truck percentage is 30% or less and low if it is greater. It was also clear that for grades of 1% or greater, the v_m value is highest when the percent trucks is lowest, it declines as the percent trucks increases, and it falls sharply in response to increases in the weight-to-horsepower ratio. This logic is reflected in the "if-then" logic presented above, including the equation that predicts v_m for grades of 1% and greater.

A more detailed examination of the trends for grades of 1% or more showed that the patterns clearly matched, especially for steeper grades. For the less-steep grades, it was also clear that the stochasticity in the simulation process makes the trends less deterministic in appearance. Thus, the strength in the model presented in the "if-then" logic is that it converges to the simulation results observed as the grades increase in severity, which is a very good property for the model to have.

The estimation of values for ΔV and β was far more straightforward. In this instance, a slight variation of Equations 28–38 was used:

$$S_a = S_{to} + (S_{ao} - S_{to})\left(\frac{e^{\frac{v-v_m}{\theta}}}{1+e^{\frac{v-v_m}{\theta}}}\right) \qquad \text{Equation 57}$$

where θ reflects the combined effects of ΔV and β. The result was:

$$\theta = \underset{30.3}{0.2551} * v_m \quad R^2 = 0.7909 \qquad \text{Equation 58}$$

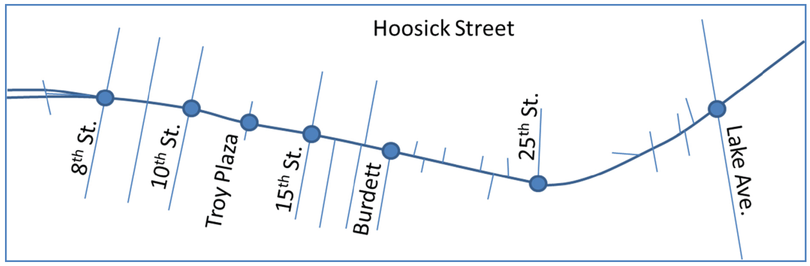
The R^2 value is 0.7909 and the coefficient for v_m is statistically significant given the t statistic of 30.3 (shown in Equation 58, just below the relevant parameter).

As with the freeways, the predictive procedure (for both PCE and truck speed) is simple and straightforward. It appears to always correctly predict not only the density that will arise in a given situation, but also both the truck and car speeds. The procedure works whether the truck flows are of a single type or mixed. It is known to work for grades from –6% to +6% and for truck percentages up to 50%.

9.6 Arterial Case Study

To illustrate application of the new arterial procedures, a real world case study was conducted. The setting is a 1.3-mile section of Hoosick Street in Troy, NY. The street is shown in Exhibit 70. The study section runs from 8th Street on the west to Lake Avenue on the east. (As an aside, this arterial lies immediately east of and connects directly to the Route 7 freeway section that was used as the freeway case study.) The study section has seven signalized intersections. They are, from west to east: 8th Street, 10th Street, Troy Plaza, 15th Street, Burdett Avenue, 25th Street, and Lake Avenue.

Exhibit 70. Case study arterial.



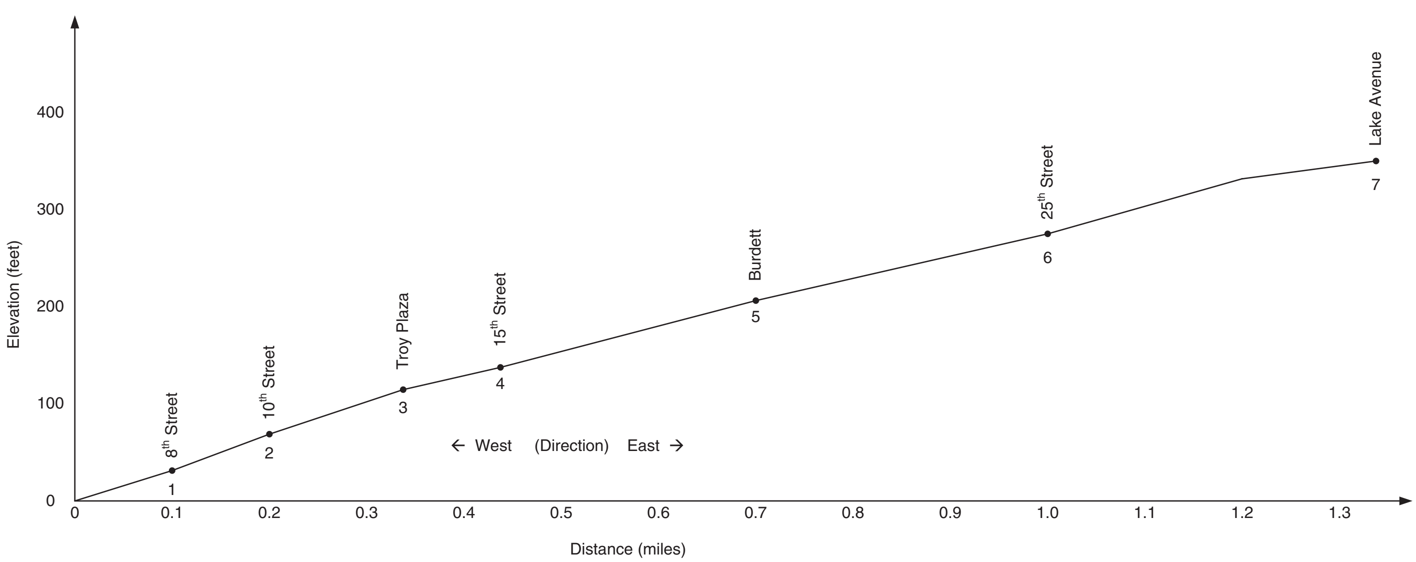
Hoosick Street has two through-lanes in each direction plus left-turn bays. The side streets have one through-lane on each approach plus left-turn bays. The percentage of trucks is about 6%. Periodically, NYSDOT does short counts including truck classifications. Otherwise, the street is not instrumented.

The uphill direction is eastbound as the street leaves the Hudson River Valley. At 8th Street, the grade is about 6%. It then increases for about a block to 7%, declines again to about 5.25% and stays at that value until just short of the end when it decreases to 1.6%. The vertical profile is shown in Exhibit 71, including the locations of the intersections.

The intersection at 8th Street is a bit complicated. On the western side, there are two entry points and two exit points on the arterial. One is the I-787 Bridge across the Hudson River. The other is the continuation of Hoosick Street (between the bridge ramps). Most of the traffic goes to and from the I-787 Bridge. A much smaller flow goes to and from Hoosick Street (from below the bridge). The entering traffic from the I-787 Bridge is traveling at 40–50 mph as it approaches the signal at 8th Street. The traffic from Hoosick Street is going much slower, having just passed through the signal at 6th Street.

To conduct the analysis, a VISSIM simulation model of the arterial was created. It is based on data provided by NYSDOT. The model is capable of simulating fully actuated, semi-actuated/coordinated, and pre-timed operation. As with the freeway case study, the actual A.M. and

Exhibit 71. Vertical profile of the Hoosick Street case study network.



P.M. peaks have been studied as well as hypothetical situations involving near-capacity flows in both directions and 15% and 30% trucks.

The predictions of the revised HCM procedure were checked against the performance predictions provided by the VISSIM simulation model. Both directions were studied in detail, but the eastbound direction is reported here because it has the uphill grades.

It is very important to recognize that the HCM analyses were conducted with the signals disabled—that is, all of the signals were in constant green in both directions at the same time and for all controlled lefts. Undoubtedly, this will seem very strange to the reader, but it is important to realize that the HCM values being checked in this test are the running speeds of the vehicles given the grade, geometry, vehicle interactions, and so forth—*not* the overall travel times or speeds as affected by the signal timings. It turns out this can be done in a simulation model by disabling the signals. Then, as long as the model is not given any instructions about yield conditions, the traffic streams will pass by and through one another without interaction. Hence, interestingly, running times can be simulated directly.

Exhibit 72 shows the running speeds observed by segment as well as the predictions from the proposed procedure. As can be seen, the new procedure closely predicts the observed values. The correspondence is always close between the simulated (observed) and predicted (New HCM model) running speeds.

9.7 Truck Speeds through Roundabouts

The objective of this task was to develop methods to estimate truck speeds through roundabouts (as distinct from either the passenger car speeds or mixed traffic speeds). To conduct these analyses, the team had access to all of the videotapes and datasets prepared as part of the research for *NCHRP Report 572: Roundabouts in the United States* (Rodegerdts et al., 2007). These data encompass information related to many single lane roundabouts nationwide and a few multilane roundabouts. Excel workbooks were created for every approach that was studied. Moreover, one tab in each workbook shows the sequence of vehicle events that took place including a field that indicates whether each vehicle was an automobile, motorcycle, small truck, or large truck. A small truck was considered to be a single-unit truck, a single-unit camper, or a delivery van. A large truck was a multiple-unit truck such as a tractor-trailer, a car or truck towing a boat or trailer, or a bus.

9.7.1 Analyses

Three analyses have been conducted regarding trucks at roundabouts. The first examined move-up times to estimate truck PCEs. The second looked at the entry capacity equation to see how the percentage of trucks affected its calibration. The third examined the impact of facility geometry on truck speed. These studies have been conducted on the basis of data from two of the roundabouts studied in *NCHRP Report 572*: the single-lane roundabout in Lothian, MD, and the double-lane roundabout in Brattleboro, VT. These two were examined most intensely because they had the highest truck flow rates.

Because the video recording technology in the *NCHRP Report 572* project made use of a special omni-directional camera, it is possible to trace individual vehicles through the roundabouts. To learn more about truck speeds through roundabouts, these omni-directional recordings were reviewed for two roundabouts, one single lane and one double lane, to collect information about individual truck trajectories. Automobile trajectories were also collected for comparison.

Exhibit 72. The new HCM procedure versus the simulation model results for the Hoosick Street case study.

Data Item	Eastbound Segments					
	8th-10th	10th-TP	TP-15th	15th-BD	BD-25th	25th-Lake
Number of Lanes	3	3	2	2	2	2
Length (ft)	531	797	521	1312	1430	1725
Grade (%)	6.89%	5.55%	5.32%	5.25%	4.90%	4.26%
PM Peak, 6.1% Trucks						
Flow Rates (vph)						
Trucks	75.8	75.8	75.6	75.5	75.5	75.5
Autos	786.6	721.8	662.3	603.0	729.9	611.1
Total	862.4	797.5	737.9	678.5	805.4	686.6
Flow Rate (vphpl)	287.5	265.8	368.9	339.3	402.7	343.3
Running Speed						
Autos (mph)	44.1	44.1	44.4	44.4	45.0	44.7
Trucks (mph)	42.0	41.0	42.0	42.3	43.6	43.5
Average (mph)	43.9	43.9	44.2	44.2	44.9	44.6
New HCM Model						
Autos (mph)	43.6	42.4	42.6	43.1	43.4	43.4
Trucks (mph)	43.2	41.4	41.5	42.4	43.3	43.4
Average (mph)	43.5	42.3	42.5	43.1	43.4	43.4
PM Peak, 15% Trucks						
Flow Rates (vph)						
Trucks	176.6	176.5	176.4	176.1	175.9	175.9
Autos	714.3	661.1	608.9	559.8	685.3	582.1
Total	890.9	837.6	785.3	735.9	861.1	758.0
Flow Rate (vphpl)	297.0	279.2	392.6	367.9	430.6	379.0
Running Speed						
Autos (mph)	44.0	43.9	44.0	44.1	44.7	44.6
Trucks (mph)	41.5	40.5	41.4	41.8	43.1	43.2
Average (mph)	43.6	43.3	43.6	43.7	44.5	44.4
New HCM Model						
Autos (mph)	43.5	42	42.2	42.8	43.2	43.3
Trucks (mph)	43.2	41.3	41.2	42.2	43.1	43.3
Average (mph)	43.5	41.9	42.1	42.7	43.2	43.3
PM Peak, 30% Trucks						
Flow Rates (vph)						
Trucks	364.8	364.6	364.5	364.0	363.4	363.1
Autos	583.1	546.8	509.9	472.4	599.8	535.8
Total	947.9	911.4	874.4	836.4	963.1	898.9
Flow Rate (vphpl)	316.0	303.8	437.2	418.2	481.6	449.4
Running Speed						
Autos (mph)	43.4	42.8	43.4	43.4	44.2	43.7
Trucks (mph)	40.9	39.7	40.8	41.2	42.5	42.4
Average (mph)	42.6	41.8	42.6	42.7	43.6	43.3
New HCM Model						
Autos (mph)	43.2	41.2	41.3	42.0	42.8	43.0
Trucks (mph)	43.0	40.9	40.8	41.6	42.7	43.0
Average (mph)	43.1	41.1	41.1	41.9	42.7	43.0

A set of monitoring points was superimposed on the omni-directional videotape images (Exhibit 73). There are two on each approach so that move-up times could be observed. Similarly, two data collection points lie on each exit. Finally, eight data collection points are on the circulating roadway: four in-between the legs of the roundabout and four at the midpoint of each splitter island.

Individual vehicles were followed as they passed through the roundabouts, and timestamps were recorded when the monitoring points were passed. Hence, for example, a vehicle entering at 2 and exiting at 9 would have nine timestamps: at 2, 2, R, T, Y, U, I, 9, and 9. Distances were measured between the data collection points so that speeds (and travel rates) could be computed between all pairwise combinations of monitoring points (e.g., 2R, R7, RT, TY, Y8, YU . . .).

It is important to note that the videotapes were created during time periods when the roundabout was at or near capacity. The *NCHRP Report 572* data collection team aimed to collect data when there was a standing queue on one or more approaches. Hence, most vehicles will be entering the roundabout from a speed near zero.

A fundamental relationship related to facility design gives a sense of how the facility design relates to the speeds trucks "should" be able to travel:

$$v^2 = gR(e+f) \qquad \text{Equation 59}$$

where

v^2 = the square of the vehicle speed,
g = the gravitational acceleration rate,
R = the radius of the trajectory followed by vehicles through the roundabout,
e = the super-elevation (typically negative for drainage), and
f = the friction coefficient.

Exhibit 73. Data collection points in the roundabouts.

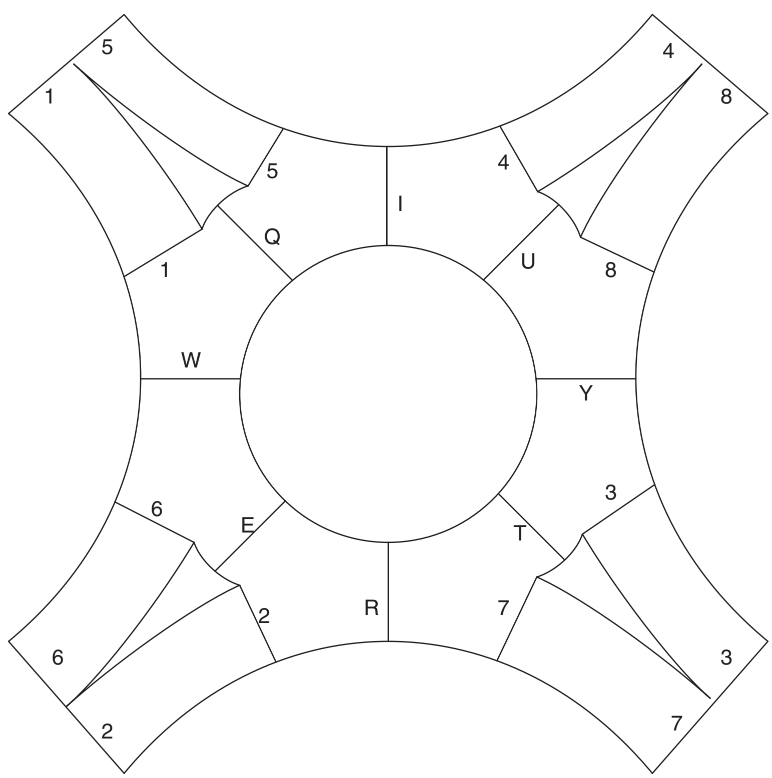


Exhibit 74. Recommended diameter, radius, and speed relationships for roundabouts.

	Approximate R4 Value – Radius for Conflicting Left-Turn Movement		Maximum R1 Value – The Entry Path Radius	
Inscribed Circle Diameter (ft)	Radius (ft)	Speed (mph)	Radius (ft)	Speed (mph)
Single-Lane Roundabout				
100	35	13	165	25
115	45	14	185	26
130	55	15	205	27
150	65	15	225	28
Double-Lane Roundabout				
150	50	15	205	27
165	60	16	225	28
180	65	16	225	28
200	75	17	250	29
215	85	18	275	30
230	90	18	275	30

Adapted from Exhibit 6-14, *Roundabouts: An Informational Guide* (FHWA, 2000).

In FHWA's roundabout design guide, *Roundabouts: An Informational Guide,* this relationship is employed to develop guidelines for roundabout diameters and vehicle speeds. Exhibit 74 shows the numerical guidance presented in Exhibit 6-14 of the guide (FHWA, 2000). The speed for R_1 pertains to non-stop vehicles entering the roundabout; the speed for R_4 is for vehicles navigating the circulating roadway. The speed for R_4 is the speed that corresponds to the analyses presented here.

One of the two roundabouts studied for speeds was the single lane roundabout in Lothian, MD. It has an inscribed circle diameter of 120 ft., which means the speed of vehicles on the circulating roadway should be about 15 mph.

Exhibit 75 shows the distributions of entering and circulating speeds observed for the Lothian roundabout. Entering speeds were based on first entry movements (e.g., 2R) and right-hand exit movements (e.g., R7) while circulating speeds were based on movements between subsequent monitoring locations in the roundabout (e.g., YU, UI, IQ). The right-hand exit movements were more similar to the entering movements than to the circulating movements.

The speeds are clearly different for trucks than for automobiles. In the case of entry speeds, the 80th percentile for large trucks is about 3 mph, while it is about 17 mph for automobiles.

Exhibit 75. Distributions for entering and circulating speeds—Lothian single-lane roundabout.

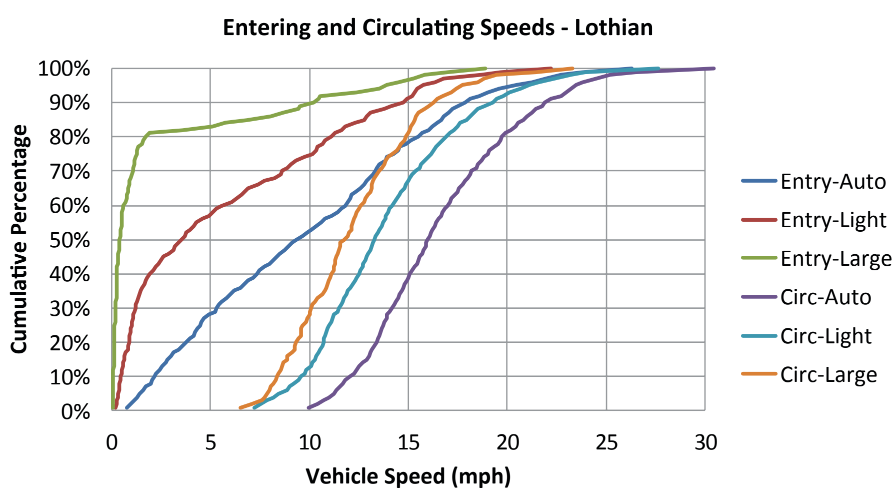
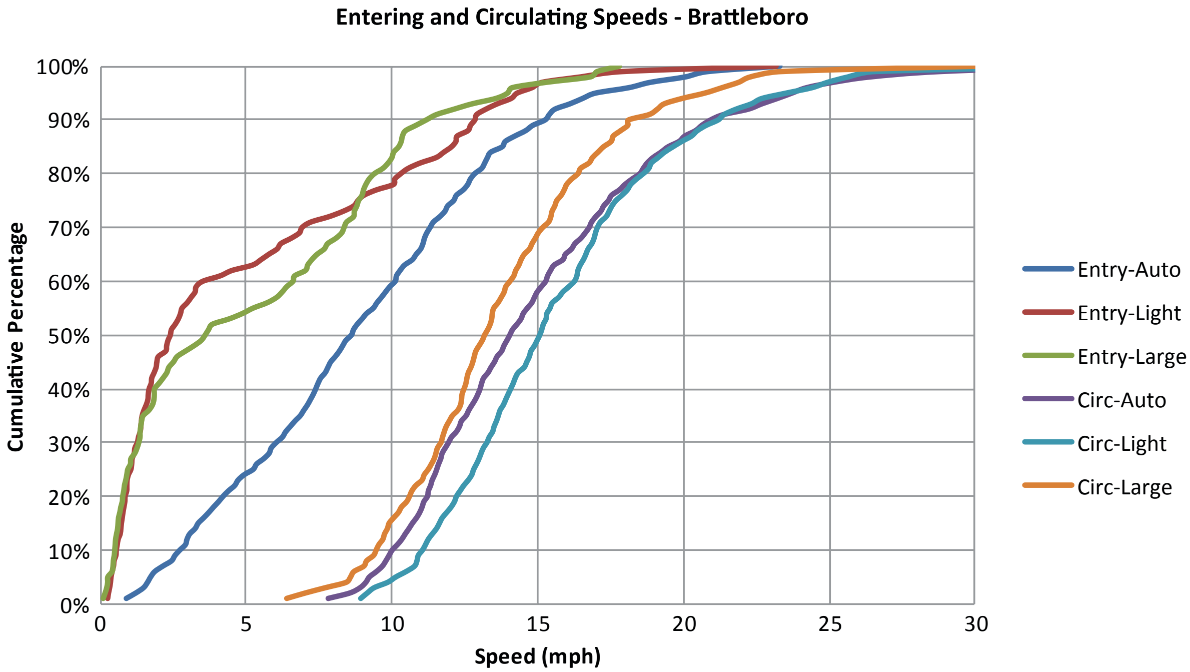


Exhibit 76. Distributions for entering and circulating speeds—Brattleboro double-lane roundabout.



The differences in speeds on the circulating roadway are not quite so dramatic. Here the 80th percentile for large trucks is 15 mph, while for automobiles it is 20 mph. At about the 50th percentile, the speeds match the value shown in the roundabout guide, which is what should have been found.

The conclusion to draw is that the speeds of trucks are clearly different from the automobiles. On entering the facility, they are strikingly different. On the circulating roadway they are less different, but still not the same.

Exhibit 76 shows the same information for the two-lane Brattleboro roundabout. Again, the entry speed distributions for trucks are significantly different from the automobiles—for example, the 60th-percentile speed for the large trucks is about 3 mph, while it is 12 mph for the automobiles. The circulating speeds are more similar. The 80th-percentile speed for trucks is 16 mph, while for automobiles it is 18 mph.

It seems clear that these differences in speeds should be reflected in the HCM procedures, in terms of estimating delays for trucks as they pass through isolated roundabouts, and for trucks versus automobiles as they traverse roundabouts in arterials.

The field data obtained from two roundabouts (one single, one double) where the truck flows were significant, suggest that truck speeds upon entry are significantly different from and slower than automobile speeds, but the circulating speeds are fairly similar although the truck speeds are clearly lower than the automobile speeds.

9.8 Arterial Truck Travel Time Reliability

Existing truck travel time reliability for one or more selected segments of an arterial street can be obtained from the National Performance Management Research Dataset (NPMRDS) for the National Highway System (NHS) (FHWA, 2013, June 26).

Resources did not permit the development of a model for predicting truck travel time reliability. However, the SHRP2-L08 methodology (Kittelson and Vandehey, 2012) can be used to estimate mixed flow travel time reliability. Until such time as better methods become available, the SHRP2-L08 results might be used as a proxy for truck travel time reliability.

9.8.1 Data on Existing Truck Reliability—NPMRDS

NPMRDS contains archived data on truck travel times by highway segment on the NHS, by 5-min-long time periods of the day. It is a vehicle-probe based data set. Separate travel times are reported for FHWA Vehicle Classes 7 and 8 (labeled "trucks" in the database), all other vehicle classes (labeled "passenger vehicles"), and all vehicles combined. The number of vehicles and the percent of trucks in the data are not reported. Historic data is available for non-Interstate highways on the NHS back to July 2013. A moderate amount of GIS database processing is required to make effective use of the data once downloaded.

9.8.2 Predicting Truck Reliability on Arterials

As for freeways, the SHRP2-L08 methodology can be used to predict mixed flow travel time reliability for urban arterial streets. It is sensitive to recurring peak-period demands, day-to-day demand variability, the frequency and severity of bad weather, crash frequency, and the scheduling of work zones on the freeway facility. The methodology can be used to predict various TTIs, of which the 50th-percentile and the 95th-percentile TTIs are required.

The median (50th-) and 95th-percentile TTIs predicted using the SHRP2-L08 method are entered into the following two equations, which are solved for the values of the parameters *k* and *c*:

$$TTI(50\%) = \sqrt[c]{(2)^{1/k} - 1} \qquad \text{Equation 60}$$

$$TTI(95\%) = \sqrt[c]{(20)^{1/k} - 1} \qquad \text{Equation 61}$$

The agency's target TTI threshold for on-time arrival (3.33 is recommended for arterials) is then entered into the following Burr distribution equation (along with the previously determined values of *k* and *c*) to obtain the probability *P* of on-time arrival for mixed flow traffic on the facility:

$$P_{(TTI=3.33)} = 1 - (1 + TTI^{C})^{-k} \qquad \text{Equation 62}$$

Until a better method becomes available, the mixed flow traffic reliability (probability of on-time arrival) is assumed to be the same as for trucks.

If the analyst wishes a more precise forecast, the analyst might use the SHRP2-L08 method to predict existing reliability conditions and compare that estimate with the value obtained from the NPMRDS. The ratio of the observed truck value to the estimated mixed flow value might then be used to adjust the forecasted mixed flow reliability to obtain a calibrated prediction of truck travel time reliability. However, this approach has not been tested or validated in this research.

SECTION 10

Predicting the Effect of Trucks on Capacity

This section describes the research relating to the effects of trucks on the capacity of freeways, arterial street segments, roundabouts, and signalized intersections. Recommended updates to the current HCM passenger car equivalents (PCEs) for capacity are provided.

10.1 The Freeway Truck PCE Models

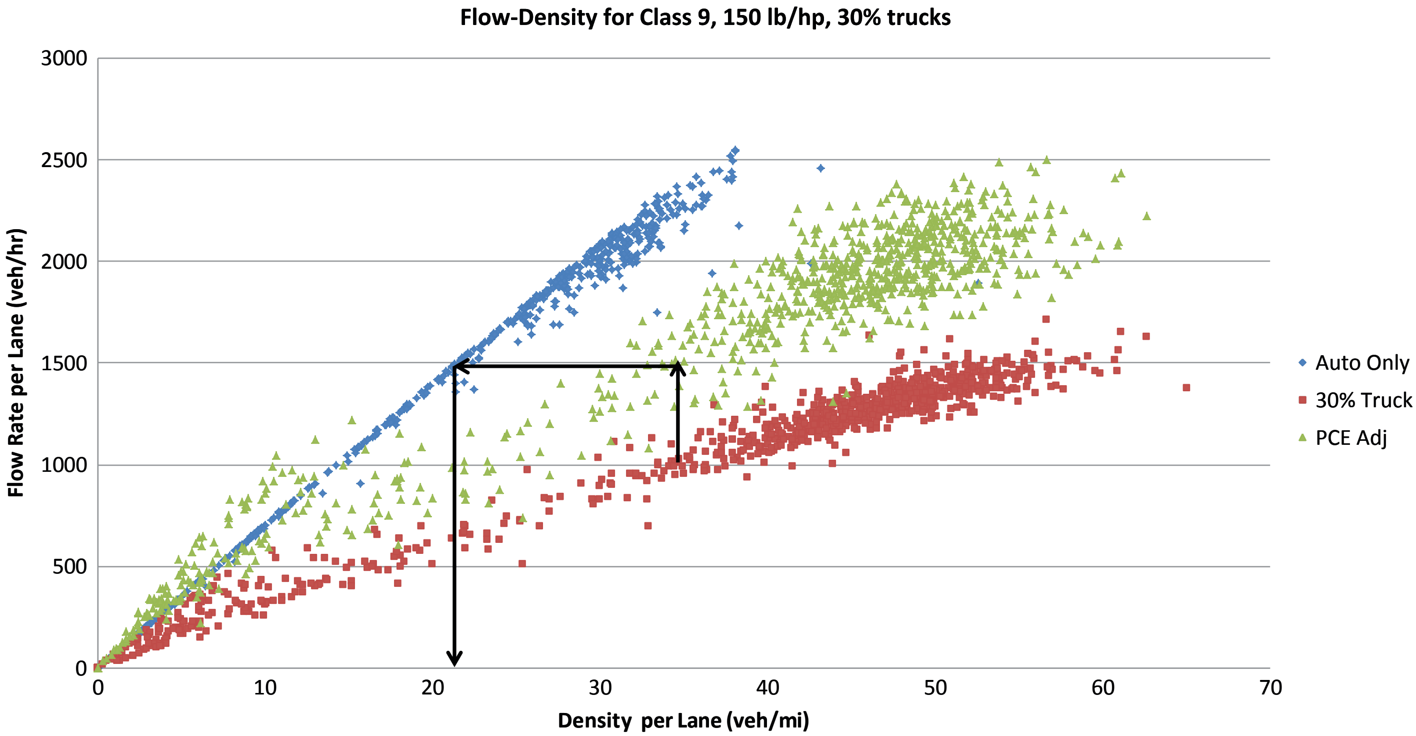
The procedures for estimating truck PCEs can be described in a simple example. Exhibit 77 shows a plot of 1-min flow-density data points for the experimental scenario that involves a 6% upgrade and 30% Class 9 trucks with a weight-to-horsepower ratio of 150 lbs/hp.

It is immediately apparent that the data points for the mixed traffic stream lie well below those for the all-automobile condition. This is consistent with the findings from analysis of the I-40 data. In addition, the speeds are very different (the slopes of the relationships). Moreover, the maximum density achieved by the mixed flow is greater than that for the all-automobile flow.

Clearly, Exhibit 77 shows the need for a PCE-based adjustment to the flow rates. The scatterplot labeled "PCE Adj" re-plots the 30% truck data points so that the maximum flow rate matches that for the all-automobile case. As shown by the sequence of solid black lines, the initial data point (35, 1500) is transformed into one that is scaled to the automobile-only maximum flow (35, 1500), and then the point on the automobile-only relationship is found that has the same flow rate (22, 1500). The resulting density is then used to determine the LOS for the mixed flow condition.

Presently, the HCM procedure converts the existing mixed flow into an equivalent all-automobile flow so that an all-automobile density can be assigned and a LOS determined. This is what the figure shows: first, the squares show the locus of the density/flow points for the actual mixed flow conditions. An appropriate PCE value was identified by determining what adjustment factor needed to be applied to create an equivalence between the 95th-percentile mixed flow rate (about 1500 veh/hr/lane) and the all-automobile 95th-percentile flow rate (about 2400 veh/hr/lane). The effect of this mapping is illustrated by the triangular data points. The flow rates have been upward adjusted, but the densities have been unchanged. This shows how the mixed flow conditions get mapped by the HCM procedure into the all-automobile conditions, by showing that the flow rates are upward adjusted. Note that the densities are not adjusted. The current HCM procedure assumes that this mapping of the flow rates allows one to determine where the mixed flow condition lies along the continuum of all-automobile flow rates and then, based on the all-automobile conditions, to determine what equivalent all-automobile density pertains and, thereby, the LOS to assign. For example, in the case of the black lines shown, an actual mixed flow operating condition of a flow rate of 1000 veh/hr/lane and 34 veh/mile/lane is treated as being equivalent to an all-automobile condition of 1500 veh/hr/lane and 21 veh/mile/lane. This happens because the mixed flow rate of 1000 veh/hr/lane is upward adjusted to 1500 veh/hr/lane (by the PCE conversion) and then based on

Exhibit 77. Flow-density relationships on a +6% grade.



Note: +6% grade, 30% Class 9 trucks with 150 lbs/hp and an all-automobile traffic stream.

that flow rate, an all-automobile density of 21 veh/mile/lane is identified and based on that, assign a density-based LOS. The densities observed in the field are likely to always be higher than those anticipated by the all-automobile model. For practitioners, this means that they cannot take the HCM-derived density as an indication of what they should observe in the field—that is, the mixed flow rate density they observe in the field (if they observe it) will be significantly higher than the one predicted by the HCM procedure. This does not mean that the LOS is actually worse than that predicted by the HCM procedure, nor does it necessarily mean that the HCM procedure is wrong; rather, it is a reflection of the fact that the operating conditions for mixed flows (in terms of speeds and densities for a given flow rate) will be significantly different than those for an all-automobile traffic stream.

The 637 scenarios were used to create a function that predicts PCE values. The important independent variables proved to be weight-to-horsepower ratio, percent trucks, grade, and truck type (we assume because of vehicle length).

First, for each of the 520 mixed flow scenarios, a PCE value was estimated. The 95th-percentile flow rate from the automobile-only runs was used as an estimate of the facility's automobile-only capacity. The 95th-percentile flow rate from the mixed traffic runs was used as the mixed traffic capacity. These two values were then used in combination with the automobile and truck percentages to compute the PCE value:

$$f_{ao}^{s} = f_{m}^{s}\left(p_a + p_t PCE\right) \quad or \quad PCE = \frac{f_{ao}^{s} - p_a f_{m}^{s}}{p_t f_{m}^{s}} \qquad \text{Equation 63}$$

where

f_{ao}^{s} = 95th-percentile flow rate from automobile-only VISSIM runs (veh/hr);
f_{m}^{s} = 95th-percentile flow rate from mixed traffic VISSIM runs (veh/hr);

p_a = proportion of automobiles in traffic stream (decimal);
p_t = proportion of trucks in traffic stream (decimal); and
PCE = passenger car equivalent (unitless).

These PCE values and the corresponding attributes of each scenario (truck type, weight-to-horsepower ratio, etc.) were then used to derive an equation that predicted the PCE values. The result was the following equation:

$$PCE(TT) = 0.922 + 0.7632TT + 0.00799WtHp - 0.00582T\% + 0.1300G\%$$ Equation 64

where

PCE(TT) = passenger car equivalent for truck type TT (unitless);
TT = truck type (enter the FHWA Vehicle Class Number 4–13 as an integer);
$WtHp$ = weight-to-horsepower ratio (lbs/hp);
$T\%$ = truck percentage (as a decimal); and
$G\%$ = grade percentage (as a decimal).

The t statistic values for the coefficients are all greater than 1.97; therefore, all of the independent variables are relevant in predicting the PCE value. The Pearson's correlation coefficient for the equation as a whole, R^2, has a value of 0.8976, indicating a good correlation between the equation and the model run results. Note that while the PCE of a truck will vary depending on the total flow of all vehicles on the facility, the procedure described above is designed to estimate PCEs only for capacity flow.

10.2 Arterial Segment Truck PCEs

All of the 637 scenarios have been used to create a function that predicts PCE values. The important independent variables are truck type, weight-to-horsepower ratio, percent trucks, and grade.

For each of the 520 mixed flow scenarios, a PCE value has been estimated. The 95th-percentile flow rate from the automobile-only runs, f_{ao}^s, is used as an estimate of the facility's automobile-only capacity. The 95th-percentile flow rate from the mixed traffic runs, f_m^s, is used as the mixed traffic capacity. These two values are then used in combination with the automobile and truck percentages, p_a and p_t, to compute the PCE value:

$$f_{ao}^s = f_m^s\left(p_a + p_t PCE\right) \quad or \quad PCE = \frac{f_{ao}^s - p_a f_m^s}{p_t f_m^s}$$ Equation 65

These PCE values and the corresponding attributes of each scenario (truck type, weight-to-horsepower ratio, etc.) were then used to estimate an equation to predict the PCE value. The result was the following equation:

$$PCE = \underset{-5.54}{0.5006} + \underset{10.4}{0.08447}TT + \underset{15.4}{0.004475}WtHp + \underset{10.87}{.01224}T\% + \underset{9.70}{0.07621}G\% \quad R^2 = 0.7005$$

Equation 66

where

The numbers shown
below each coefficient = their respective t-statistics;
TT = the truck type (the FHWA vehicle class);
$WtHp$ = the lbs/hp;
$T\%$ = the truck percentage (as a decimal); and
$G\%$ = the grade percentage (as a decimal).

The *t*-critical value is 1.97. The *t*-statistic values for the coefficients are all greater than this value; therefore all of the independent variables are relevant in predicting the PCE value. The R^2 is 0.7005 as shown. Note that while the PCE of a truck will vary depending on the total flow of all vehicles on the facility, the procedure described above is designed to estimate PCEs only for capacity flow.

10.3 Creating Composite Trucks for Capacity Analysis

While an actual traffic stream is a mixture of trucks from Classes 4–13, there is no expectation that an HCM user will actually use PCE values for each type of truck when doing analyses; rather, a composite PCE should be employed. The HCM 2010 uses Equation 11–3 (in Chapter 11) (copied as Equation 67) to compute the heavy-vehicle adjustment factor:

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)} \qquad \text{Equation 67}$$

where

P_T = the percentage of trucks in the traffic stream,
P_R = the percentage of RVs,
E_T = the PCE for trucks, and
E_R = the PCE for RVs.

More generally, if the trucks and RVs are regarded simply as vehicles of type *k*, then the heavy-vehicle adjustment factor can be rewritten as Equation 68:

$$f_{HV} = \frac{1}{1 + \sum_k P_k(E_k - 1)} \qquad \text{Equation 68}$$

Simply put, $k = 1$ is for trucks and $k = 2$ for RVs.

Without loss of generality, these thoughts can be extended to a condition where there are a number of different truck types. Then Equation 68 can be rewritten as Equation 69 or Equation 70, depending upon whether there is a desire to differentiate the RVs from the trucks:

$$f_{HV} = \frac{1}{1 + \sum_{T_i} P_{T_i}(E_{T_i} - 1) + P_R(E_R - 1)} \qquad \text{Equation 69}$$

$$f_{HV} = \frac{1}{1 + \sum_{T_i} P_{T_i}(E_{T_i} - 1)} \qquad \text{Equation 70}$$

In Equation 70, the RVs are simply another truck type.

The objective of such a composite truck PCE is to create the following equivalence:

$$P_T\left(\tilde{E}_T - 1\right) = \sum_{T_i} P_{T_i}(E_{T_i} - 1) \qquad \text{Equation 71}$$

where $\tilde{E}_T$ is the composite truck PCE. Solving Equation 71 for $\tilde{E}_T$ results in the following:

$$\tilde{E}_T = \frac{\sum_{T_i} P_{T_i}(E_{T_i} - 1)}{P_T} + 1 = \frac{\sum_{T_i} P_{T_i}(E_{T_i} - 1)}{\sum_{T_i} P_{T_i}} + 1 \qquad \text{Equation 72}$$

However, since $\sum_{T_i} P_{T_i} * 1 = P_T$, then Equation 72 can be simplified to:

$$\tilde{E}_T = \frac{\sum_{T_i} P_{T_i} E_{T_i}}{\sum_{T_i} P_{T_i}} = \left(\frac{\sum_{T_i} P_{T_i} E_{T_i}}{P_T} - \frac{\sum_{T_i} P_{T_i}}{P_T} + 1 \right) = \left(\frac{\sum_{T_i} P_{T_i} E_{T_i}}{P_T} - 1 + 1 \right) \qquad \text{Equation 73}$$

Hence, $\tilde{E}_T$ is given by the percentage weighted average of the E_{T_i} values.

Application of this technique is illustrated in Exhibit 78 for a freeway. An application to an arterial would proceed similarly. Shown is the distribution of trucks by class for a situation where the trucks compose 6.1% of the overall traffic stream and the grade is level (0%).

For each truck class, the table in Exhibit 78 shows the raw percentage in the traffic stream, the average weight, average length, average horsepower, ratio of average weight to average horsepower, PCE value, and percentage of total trucks. For example, trucks in Class 5 represent 2.5% of the overall traffic stream; their average weight is 10,322 lbs; their average length is 23.23 ft.; their average horsepower is 188; their average weight to average horsepower ratio is 55; they have a PCE of 2.10; and they compose 41.2% of the trucks.

The weights, lengths, and distribution of vehicle classes in this table (Exhibit 78) were obtained from a year's worth of weigh-in-motion (WIM) data obtained from the North Carolina DOT

Exhibit 78. Developing composite PCE values for a freeway.

All Classes									
Class	ClassVar	Raw Pct	AvgWt	AvgLngth	AvgHp	Wt/Hp	Grade	PCE	TrkPct
4	4	0.7%	21325	31.75	180	118	0%	2.17	12.1%
5	5	2.5%	10322	23.23	188	55	0%	1.73	41.2%
6	6	0.5%	25733	30.09	279	92	0%	2.11	8.5%
7	7	0.1%	51879	30.46	279	186	0%	2.94	1.7%
8	8	0.8%	26090	51.09	293	89	0%	2.24	14.0%
9	9	1.1%	52670	65.20	370	142	0%	2.74	18.6%
10	10	0.0%	55095	73.64	370	149	0%	2.87	0.3%
11	11	0.0%	55554	77.74	370	150	0%	2.96	0.1%
12	12	0.2%	61147	60.79	370	165	0%	3.16	3.0%
13	13	0.0%	76439	64.67	370	207	0%	3.56	0.5%
All	6.4	6.1%	25782	38.2	252	93	0%	2.12	100.0%
Four Composite Trucks									
4	4	0.7%	21325	31.7	180	118	0%	2.17	12.1%
5-7	5.2	3.1%	14244	24.6	206	69	0%	1.86	51.4%
8-10	8.6	2.0%	41745	59.8	340	123	0%	2.55	32.9%
11-13	12.1	0.2%	63093	61.8	370	171	0%	3.21	3.6%
All	6.4	6.1%	25896	38.4	253	96	0%	2.15	100.0%
Two Composite Trucks									
4-7	5.0	3.9%	15597	26.0	201	78	0%	1.90	63.5%
8-13	8.9	2.2%	43521	59.5	340	128	0%	2.61	36.5%
All	6.4	6.1%	25782	38.2	252	96	0%	2.14	100.0%
One Composite Truck									
4-13	6.4	6.1%	25782	38.2	252	93	0%	2.12	100.0%

Note: The above example is applicable for 6% trucks on level terrain (0% grade).

for the WIM station located on U.S. 421 just south of the interchange with U.S. 64 in Siler City, North Carolina, for the 2004 calendar year. A total of 654,826 vehicles were included in the sample (Stone, 2011). Weights are averages of loaded and unloaded vehicles for each vehicle class. Weights include vehicle plus cargo. The horsepower ratings by vehicle class were obtained from a doctoral thesis by Ahanotu (1999). The percentage of trucks is for the New York State Route 7 freeway at the Hudson River Bridge (Burke, 2012).

The bottom half of the table shows four different composite representations of the traffic stream. The first comprises four truck groups: 4 by itself (buses); 5–7 (single-unit trucks); 8–10 (tractors with single trailers); and 11–13 (tractors with multiple trailers). The second has two composite categories: 4–7 (single-unit vehicles) and 8–13 (tractors with one or more trailers). The third category lumps the trucks together into one group. The overall composite PCE is 2. This overall composite is the one currently recommended by the HCM procedure for freeways in level terrain.

10.4 Signalized Intersection Truck PCEs

This research task focused on development of improved truck PCEs for signalized intersections. The objective was to replace the existing single PCE value for trucks at signals with a method for estimating truck PCEs for saturation flow rate calculation at signals that enables the analyst to estimate PCE values that are sensitive to the percent of trucks (0%–100%) and the specific grade (–30% to +30%) on the approach to the signal.

10.4.1 Current HCM Method

The current HCM method for evaluating the operation of signalized intersections uses a flat 2.0 PCE for trucks in the computation of the approach saturation flow rate. There is no adjustment to the PCE value for the approach grade or different mixes of truck types (single-unit or semitrailer).

10.4.2 Approach

Several studies have investigated the discharge characteristics at signalized intersections and proposed PCE values. Most of these studies involved field data collection of saturation headways of passenger cars and trucks at the intersection approaches to determine PCE values. There was no investigation of truck characteristics or intersection design features (notably approach grade) on the PCE values.

A comprehensive review is provided by Washburn and Cruz-Casas (2010). They developed and applied a custom simulation tool to investigate the impact of the proportion of trucks, truck size, and truck position in the queue. They suggested PCE values of 1.8, 2.2, and 2.8 for small, medium, and large trucks, respectively. Boltze (2006) reported saturation flow rates for the approaches to signalized intersections under different grades. He found an effect with both grade and the percent trucks.

A major challenge in empirical studies for determining truck impacts on saturation flows at signalized intersections is the difficulty of finding appropriate study locations: measurements of saturation flow per HCM require at least eight vehicles in the queue plus a significant proportion of truck traffic in order to have multiple trucks in the queue for a sufficient number of cycles. These conditions are difficult to be met especially at locations with high grades. So, the simulation approach was chosen to determine how truck proportion and approach grade affect the saturation flow rates at signals. Field data collected at the two intersections near the port terminals in

Oakland, California, and Miami, Florida, were used to develop and calibrate the VISSIM microsimulation program. The calibrated simulation was then applied in several scenarios to develop the truck PCE sensitive to the truck proportion and the grade at signalized intersections.

10.4.3 Simulation Development Steps

The previously discussed microsimulation model development work to develop the freeway and arterial speed models investigated and calibrated the truck footprint and speed-acceleration profiles in the VISSIM simulation. Truck acceleration profiles (acceleration versus speed) were developed for two truck classes: single-unit trucks (FHWA Vehicle Class 5) and semitrailer/combination trucks (FHWA Vehicle Class 9).

A VISSIM simulation model was coded and calibrated for each signalized intersection test site based on flows and queue lengths collected at the test sites as described in the next section. The number of required simulation replications was next determined to account for stochastic variability (10 simulation runs were used per scenario).

The calibrated VISSIM simulation was applied to obtain saturation flows for different scenarios of truck types, proportions, and approach grades. The following issues had to be addressed:

- **Truck position in the queue**: Previous research has shown that the start-up lost time and saturation flow depend on the truck position in the queue in addition to the type and proportion of trucks. Different PCE values result for different combinations of truck positions in the queue (Washburn and Cruz-Casas, 2010). However, such data are difficult to collect in practice. Furthermore, queue position by vehicle type and the associated discharge headway are not standard outputs by VISSIM and other simulation programs.
- **Number of queued vehicles**: HCM requires that there are at least eight vehicles in the queue to reliably obtain saturation flows, of which the first four vehicles (headways) are used in the calculation of the start-up lost times. In typical undersaturated conditions, stochastic volume variations may result in shorter queues and result in errors in the predicted saturation flows.

To account for both these issues, the predicted discharge rate (in veh/h) of the through movement from the simulation was used as the primary output for getting the PCE values. To obtain the discharge rate from the VISSIM simulation, the input approach volume was increased to exceed capacity to ensure a continuous queue. The discharge rate or capacity (c) is then obtained from the detector recorded volume. The detector is placed just downstream of the intersection stop line.

The saturation flow rate S (veh/h/green) is calculated from

$$S = \frac{c}{\left(\frac{g}{C}\right)} \qquad \text{Equation 74}$$

where c is the discharge rate (veh/h) and g/C is the green time per cycle ratio for the intersection approach. The heavy-vehicle adjustment factor f_{hv} is calculated from

$$f_{hv} = \frac{S}{S_b} \qquad \text{Equation 75}$$

where S is the saturation flow rate (veh/h/green) and S_b is the baseline saturation flow (0% trucks on flat grade). The PCE value is calculated from the heavy-vehicle adjustment factor f_{hv} as follows:

$$\text{PCE} = \left(\frac{100}{f_{hv} \times P_{hv}} - \frac{100}{P_{hv}}\right) + 1 \qquad \text{Equation 76}$$

where P_{hv} is the proportion of heavy vehicles (%) and f_{hv} is the heavy-vehicle adjustment factor.

Selection of Test Sites

Two test sites were selected, both at major maritime ports, so as to obtain high semitrailer truck volumes. The Maritime Street site is located on a major access road to the Port of Oakland, California. The Biscayne Boulevard site is located on the main access road to the Port of Miami. Being maritime port sites, both sites had flat (0%) level grades. Field observations at both sites indicated that queues rarely approached eight vehicles in length; thus, field measurement of saturation flow rates was ruled out.

Test Site 1: Maritime Street, Oakland, California. Field data were collected on Wednesday, March 13th, 2013, at a signalized intersection at Maritime and 14th Streets close to the port of Oakland, California. The site had a very high proportion of trucks (83% of the total volume), most of which were semitrailer trucks. A VISSIM simulation of the test site was developed and calibrated based on the field collected data. The calibration consisted of adjustment of driver model parameters and truck fleet characteristics based on the approach described in the previous section. Comparison of the measured and VISSIM predicted counts and saturation flows showed close agreement. Most of the discrepancies were found on movements not essential for this application (e.g., left turns). Note that VISSIM predicted higher saturation flows for 100% passenger cars (2,200 vehicles per hour of green [vphg]/lane vs. the ideal saturation flow of 1,900 vphg/lane in the HCM 2010). The northbound approach of Maritime at 14th Street was selected to obtain the discharge flow rate, saturation flows, and PCE values according to the above described approach.

Test Site 2: Biscayne Boulevard, Miami, Florida (Validation Site). The above described methodology was applied at a second location, Biscayne Boulevard in Miami, Florida. All trucks to and from the port of Miami pass through the intersection of Biscayne Boulevard with NE 5th Street and NE 6th Street. Data were collected at the intersections of eastbound NE 5th Street with southbound Biscayne Boulevard and westbound NE 6th Street with northbound Biscayne Boulevard on Tuesday, April 16th, 2013, between 8 A.M. and 10 A.M. The data collection at this site consisted of

- Turning movement counts;
- Length of green time, red time, and amber time for individual cycles (in seconds);
- Total number of departures for the cycle (i.e., number of vehicles crossing the stop bar, including through, left, and right turning vehicles) broken down by vehicle class;
- Stopped vehicles in queue at the start of green (i.e., number of vehicle in queue before the first vehicle crosses the stop bar at the beginning of green) broken down by vehicle class;
- Stopped vehicles in queue at the start of red (i.e., number of vehicles in queue at the end of green which could not be serviced during the cycle); and
- Other events (crashes, double parking, jay-walking, etc.).

A VISSIM simulation was created for the Miami site for the intersection at Biscayne Boulevard (north–south) and Port Boulevard/NE 6th Street (east–west). The truck characteristics and other settings were identical to the Maritime Street VISSIM simulation. Comparison of field measured flows and queues in the westbound direction indicates that the simulation model reasonably replicates observed conditions. The differences between measured and simulated volumes were less than 1%, and the difference in simulated and field observed queue lengths was about 8%.

Exhibit 79 shows the simulation model predicted sample saturation flows and PCE values obtained at the two test sites. It can be seen that they are in close agreement.

Sample Tests

First, a series of tests were performed to verify that the simulation was working correctly for one scenario of weight-to-horsepower ratio (equal to 150 lbs/hp). These tests are described below.

Exhibit 79. VISSIM predicted saturation flows and PCE values at the two test sites.

% Trucks	Maritime Street			Biscayne Boulevard		
	Sat. Flow	f_{hv}	PCE	Sat. Flow	f_{hv}	PCE
0	2,224	1.00	1.00	2,166	1.00	1.00
25	1,735	0.78	2.13	1,634	0.75	2.30

Sample Test 1—Variation of Truck Proportion under a Fixed Truck Mix. In this test the impact of the truck proportion was investigated for 0 grade. The truck mix was kept fixed as was observed in the Maritime Street test site: 10% single-unit trucks and 90% semitrailers. The proportion of trucks varied from 0% to 83%. The predicted PCE values are shown in Exhibit 80.

The predicted PCE values are higher than the HCM 2010 value of 2.0 and the difference of PCE values is small for a wide range of truck proportions. Note that the predicted PCE values are reasonably close to the PCE value of 2.8 proposed by Washburn and Cruz-Casas (2010) for the given vehicle mix.

Sample Test 2—Variation of Truck Mix under a Fixed Truck Proportion. In this test, the proportion of trucks was kept fixed at 25% and 0 grade. The truck mix was varied from 100% to 10% single-unit trucks. The results are shown in Exhibit 81. The results indicate as expected that PCE values are generally lower for a higher proportion of single-unit (smaller) trucks.

Developing Truck PCE Values at Signalized Intersections

Following the calibration and validation of VISSIM simulation at the two test sites and the initial simulation results, a series of simulation runs at the Maritime Street site was performed to obtain PCE values for different truck proportions, approach grades, and truck mix. Each

Exhibit 80. Sample Test 1—effect of truck proportion on PCE values.

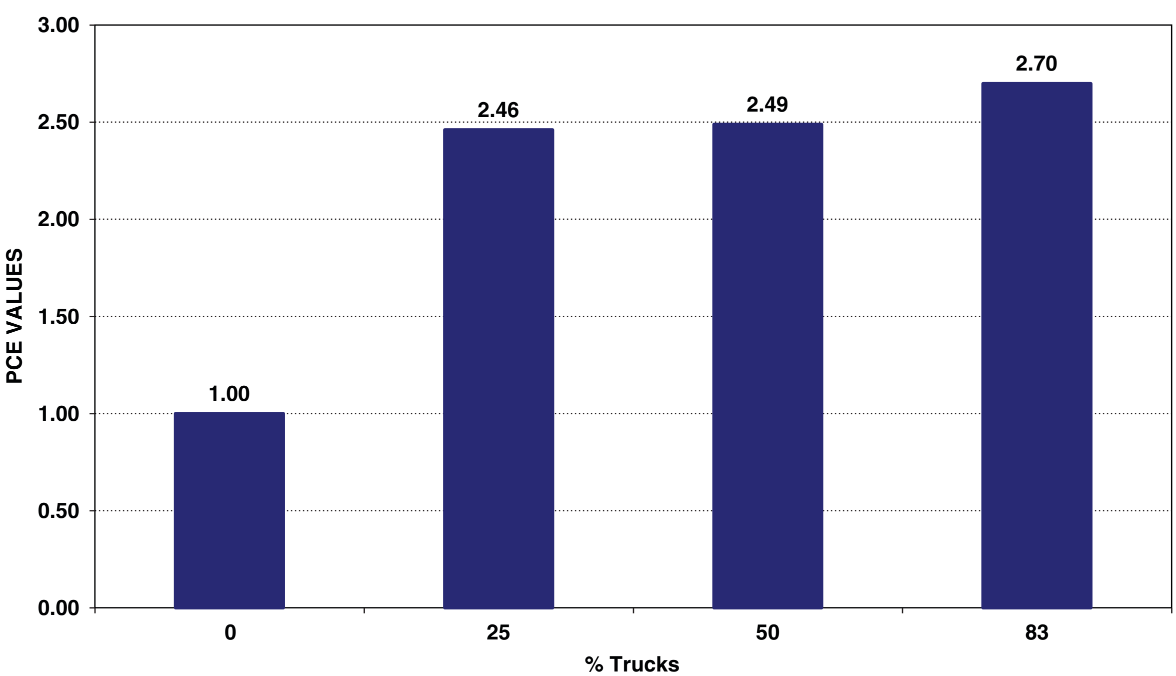
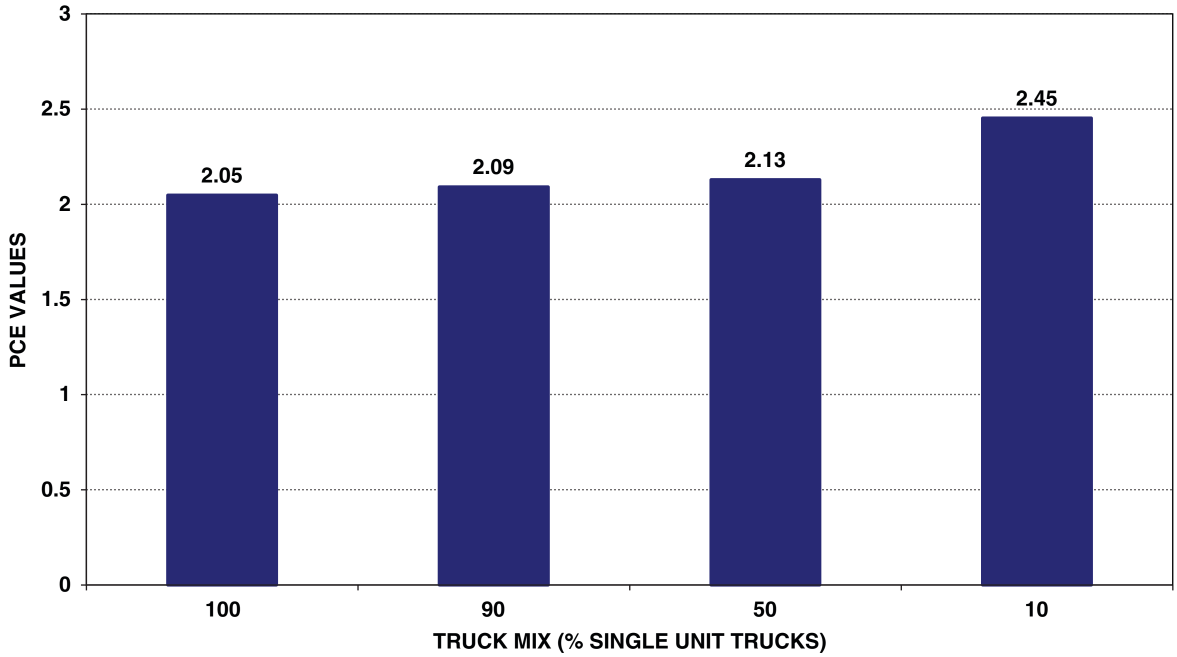


Exhibit 81. Sample Test 2—effect of truck mix on PCE values.



simulation run was replicated 10 times to account for the stochastic variability of the micro-simulation program. The following scenarios were tested:

- Weight-to-horsepower ratio: 150 lbs/hp;
- Truck mix: 50% single-unit trucks, 50% semitrailer trucks;
- Truck proportion: 10%, 20%, 30%, 40%, 50%; and
- Grade: –4%, –2%, 0, 2%, 4%, 6%, 8%, 10%.

Effect of Grade and Truck Proportion. Exhibit 82 shows the impacts of truck proportion and grade on the base saturation flow rate (all passenger cars, flat grade). These findings are close to results reported earlier in the literature. Several statistical models were fitted to the resulting simulation data to predict the reduction in the saturation flow rate because of the truck proportion and grade. The following model was selected based on the best goodness-of-fit (R^2) value and reasonable behavior for both negative and positive grades. A comparison of simulated and predicted values for this model is shown in Exhibit 83.

- For Negative Grades (G<0%)

$$\%\text{ Base Saturation Flow} = 100 - 0.79 * T - 2.07 * G$$

- For Positive Grades (G≥0%)

$$\%\text{ Base Saturation Flow} = 100 - 0.78 * T - 0.31 * (G^2) \qquad \text{Equation 77}$$

where

% Base Saturation Flow = the change in saturation flow rate from standard conditions (0% grade, 0% truck);

T = % of heavy vehicles in traffic stream (expressed as %)(e.g., 1% trucks is expressed as 1.00); and

G = grade (%) ratio of vertical climb to horizontal reach (+ for upgrade, – for downgrade) expressed as a percent (e.g., 1% grade is expressed as 1.00).

Exhibit 82. Saturation flow rate by grade and truck% for 50:50 mix Class 5 and Class 9 trucks.

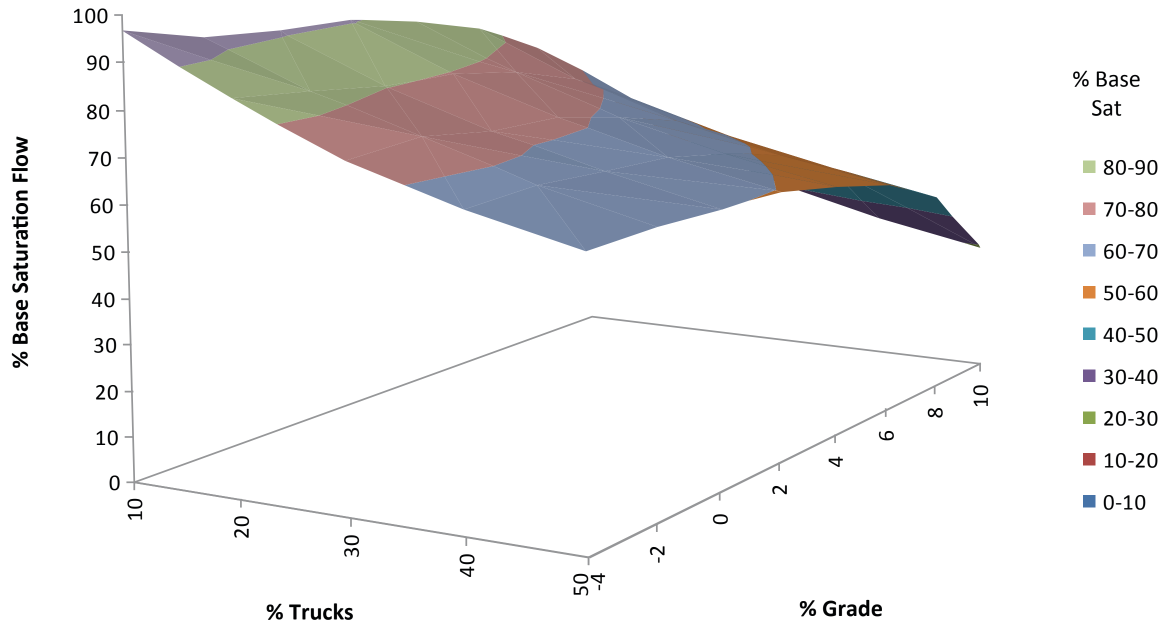


Exhibit 83. Comparison of the predicted and simulated reductions in saturation flow.

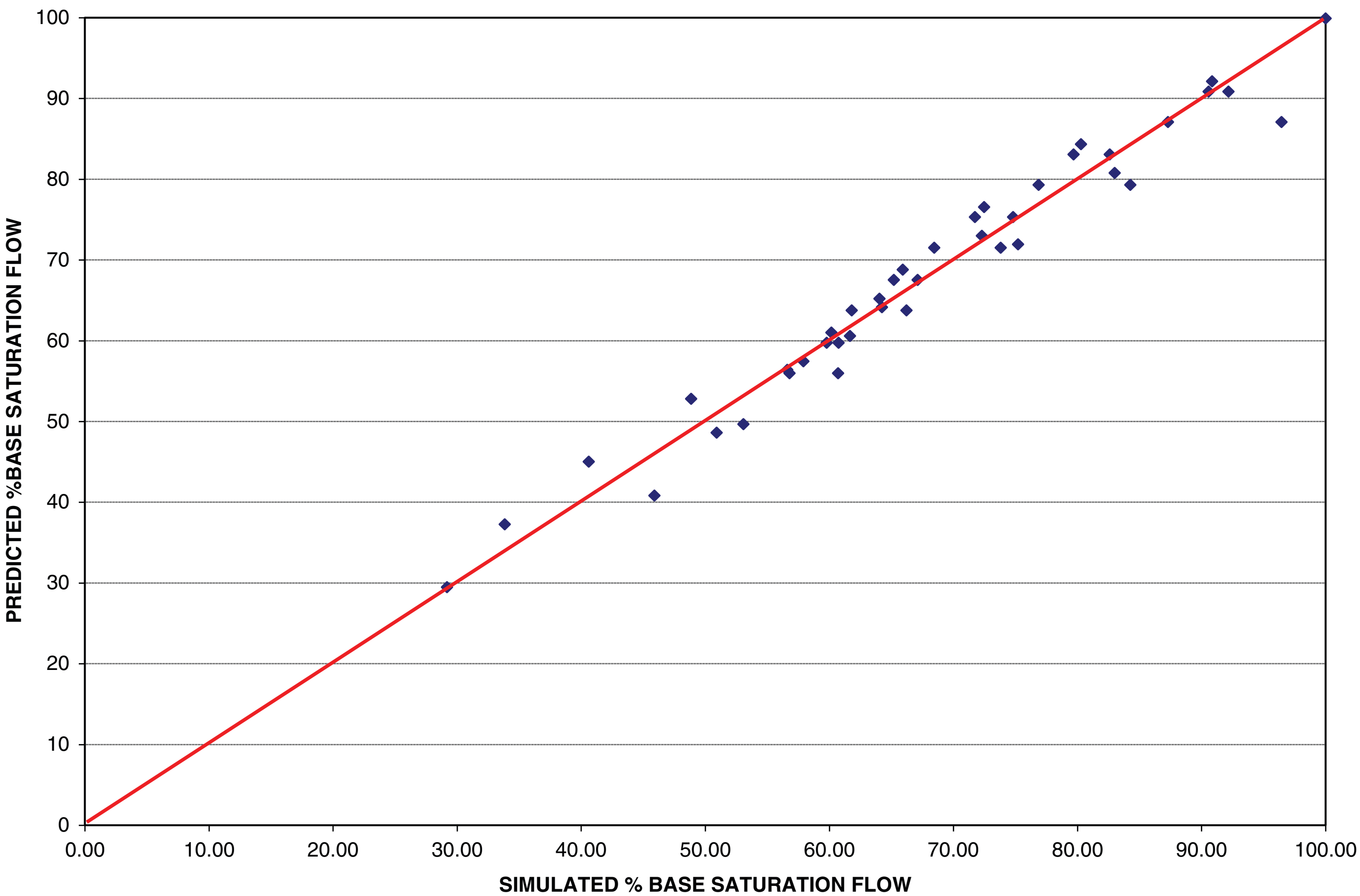
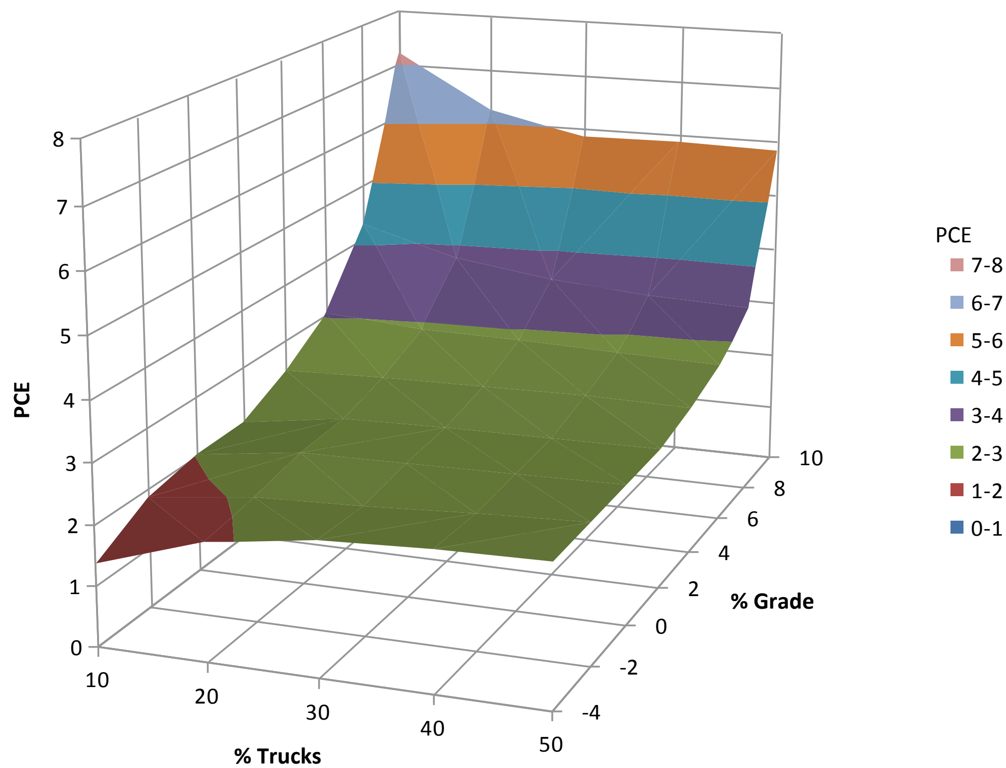


Exhibit 84. Signalized approach PCE values—50:50 Class 5:Class 9 trucks.



This model is valid for the range of trucks between 0% and 50% of the traffic stream, for grades between and including –4% and +10%.

Exhibit 84 shows the predicted PCE values for the same mixture of grades and truck proportions. Note that the highest PCE value was obtained for a low proportion (10%) of trucks and the maximum grade of 10%. This has been also the case for the PCE value reported in the HCM 2010 for specific grades on freeways (see Exhibit 11-11 of HCM 2010). This is because under higher truck proportions, truck platoons are formed and the impact of a single truck in a platoon of trucks is less severe than the impact of a single truck traveling in a traffic stream of passenger cars. Note also that the PCE values are very similar for high truck percentages for all grades tested.

10.4.4 Effect of Truck Mix

The simulation runs were for the repeated scenarios of truck proportions and approach grades under a different truck mix (75% Class 5 single-unit trucks and 25% Class 9 semitrailers). In addition, the simulation was run for two additional truck proportions: 1% and 5%. The resulting PCE values are shown in Exhibit 85.

The results confirmed the earlier findings that the highest PCE values for trucks are obtained under low truck proportions and high grades; as shown in Exhibit 85, the predicted PCE value for 1% trucks is 11.3.

Exhibit 86 illustrates the impacts of the truck mix on the PCE values for different approach grades and 10% proportion of trucks. On the average, the difference in the predicted PCE values is about 6%. Overall the differences in the reduction of saturation flow and PCE values due to the different truck mix ranged from 5% to 8% for all combinations of truck proportions and approach grades.

Exhibit 85. Signalized approach PCE values—75% Class 5 and 25% Class 9 trucks.

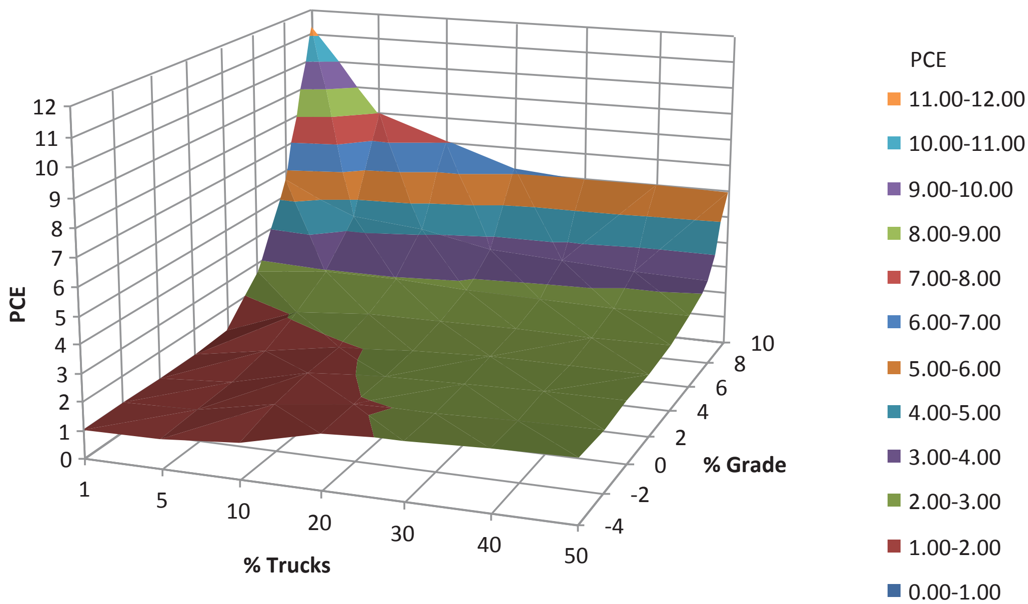
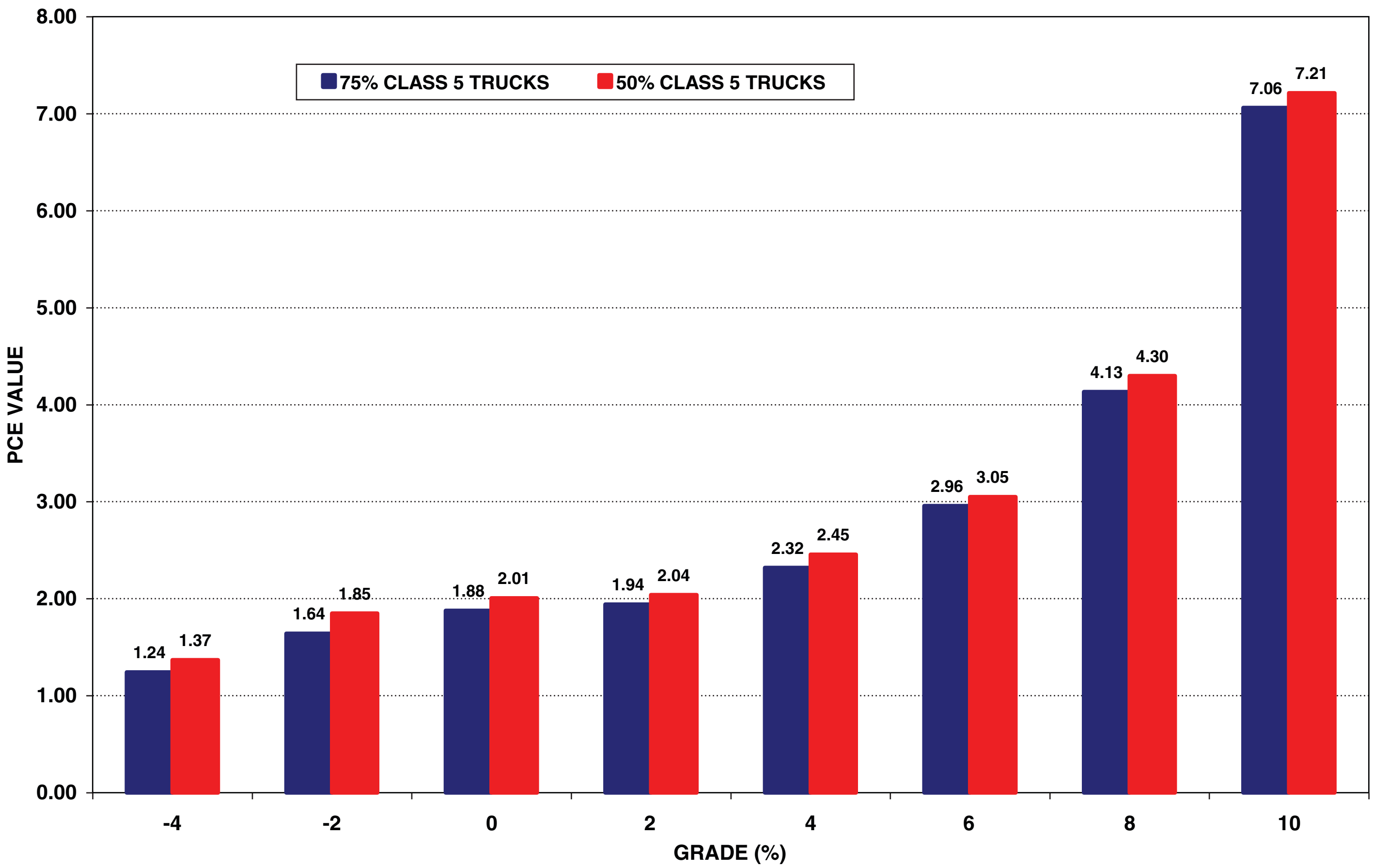


Exhibit 86. Impact of truck mix on PCE values—10% proportion of trucks.



10.4.5 Comparison with HCM Signalized Intersection Truck PCEs

The findings from the analysis of the simulation results indicate that the PCE values at signalized intersections depend on the truck characteristics, proportions, and approach grade. The impacts of trucks on saturation flows (and capacities) at traffic signals are higher than the HCM 2010 estimates under the single PCE value of 2.0. This is illustrated in Exhibit 87 where the simulated and HCM 2010 heavy-vehicle adjustment factors (f_{hv}) are compared for all the tested scenarios.

10.4.6 Comparison with HCM Signalized Intersection Saturation Flow Adjustment

The HCM 2010 method currently has two relevant saturation flow adjustment factors related with truck effects. One factor focuses on trucks exclusively. A separate saturation flow adjustment factor is used for grade, and it is independent of the percent of trucks. Consequently, it is necessary to consider both the PCE and grade effects in the HCM method. In the HCM, the combined effects of the heavy-vehicle PCE and grade on signalized intersection saturation flow rates are computed according to Equation 78 using the HCM recommended PCE of 2.0 (taken from Equation 18-5 of the HCM):

$$f_{HV} * f_g = \frac{100}{100 + (HV\%)} * \frac{200 - (G\%)}{200} \qquad \text{Equation 78}$$

where

$f_{HV} * f_g$ = the combined effect of percent trucks and grade on saturation flow (ratio of adjusted to ideal saturation flow);

Exhibit 87. HCM 2010 versus VISSIM simulated heavy-vehicle adjustment factors—all tested scenarios.

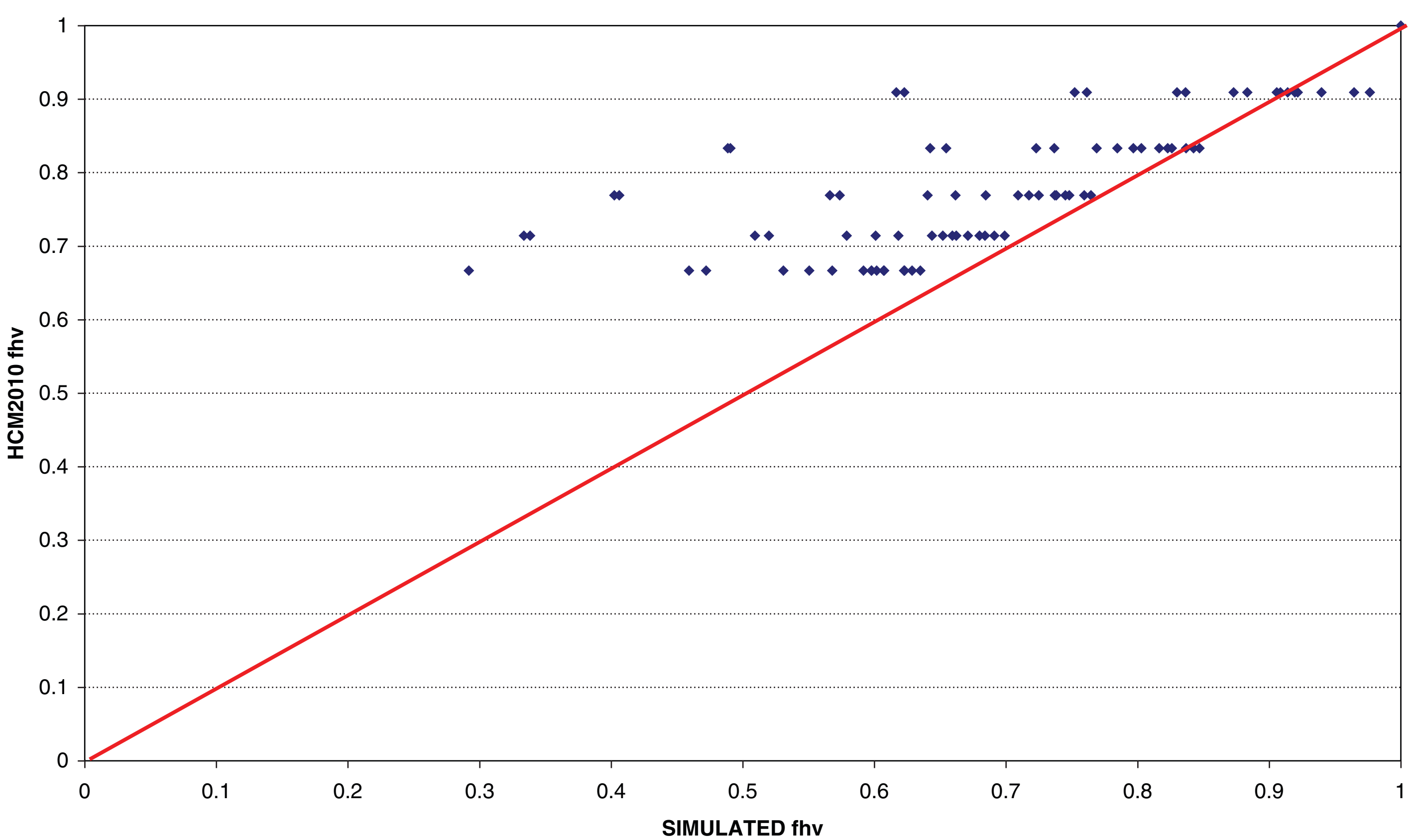
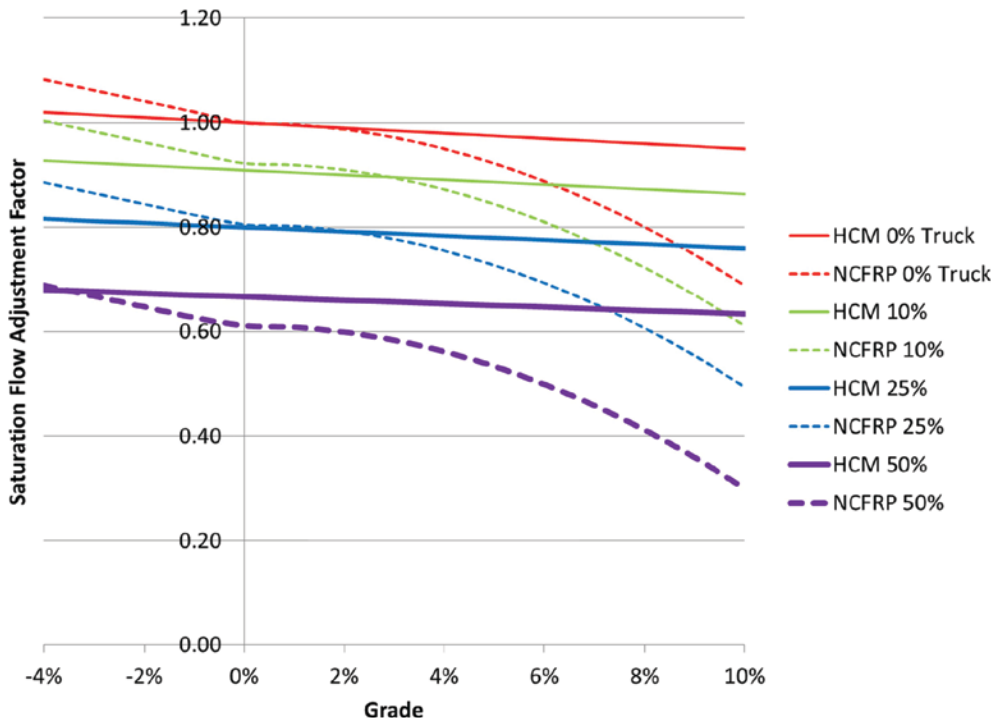


Exhibit 88. Recommended saturation flow adjustments compared with HCM truck and grade adjustments.



$HV\%$ = the percentage of heavy vehicles in traffic stream (%); and
$G\%$ = the percent grade (%)(+ for upgrade, – for downgrade).

Exhibit 88 compares the saturation flow rate adjustments produced by the HCM for grades and percent trucks combined (Equation 78) with the truck and grade percentages produced in the simulation (as summarized in the fitted equation, Equation 77). As can be seen in Exhibit 88:

- The HCM adjustments for grade and percent trucks combined are similar to the recommended NCFRP model (Equation 77) in the range of 0% to 2% positive grades, as long as the percent of trucks in the traffic stream is below 40%.
- The recommended model diverges significantly from the current HCM method for negative grades and for positive grades above 2%. The HCM method appears to underestimate the effects of higher grades on saturation flow rates at signals. The HCM also underestimates the effects of negative grades on saturation flow.
- The recommended model diverges significantly from the HCM for truck percentages in excess of 40%, regardless of the grade or lack of grade.

10.5 Roundabout Intersection Truck PCEs

10.5.1 Existing Truck Treatment

The roundabout method in the HCM uses a gap acceptance model in which the capacity of the entry (c_{entry}) is determined by the conflicting flow rate on the roundabout ($v_{conflicting}$):

$$c_{entry} = 1{,}130 * e^{-.001 * v_{conflicting}} \quad \text{Equation 79}$$

The entry capacity is in passenger cars/h and reflects an adjustment for heavy vehicles. The conflicting flow rate is in veh/h and is also adjusted for heavy vehicles. Step 2 in the methodology (shown in HCM Exhibit 21-10, which is not repeated here) makes PCE-based adjustments for heavy vehicles. The PCE is always 2.0 regardless of the heavy-vehicle mix.

10.5.2 Approach

The objective of this task was to update and expand the PCE values for trucks so that the gap acceptance model produces capacity estimates that are consistent with field conditions involving various mixes of trucks.

Our expectation was that heavy vehicles would impact the saturation flow equation in both the intercept term (because trucks take more time to enter the roundabout even without conflicting traffic) and the slope parameter (because trucks need larger gaps in the conflicting traffic). It was further expected that the truck impact on the intercept term would be proportional to the impact on the slope term. In other words, the added time for a truck to enter the roundabout would be a function of geometry and classification only and would be independent of the volume of conflicting traffic. This assumption was to be tested in the data analysis and, if proven valid, would allow the use of a PCE-based flow adjustment across the entire capacity curve—albeit still being a function of grade, truck classification, roundabout diameter, and other factors. If the assumption did not hold (e.g., truck gap acceptance is impacted more than the unimpeded entry headway), we would instead incorporate truck factors directly into a revised roundabout entry capacity model.

To conduct these analyses, the team had access to all of the videotapes and datasets prepared as part of the research for *NCHRP Report 572* (Rodegerdts et al., 2007). These data encompass information related to many single-lane roundabouts nationwide and a few multilane roundabouts. Excel workbooks were created for every approach that was studied. Moreover, one tab in each workbook shows the sequence of vehicle events that took place including a field that indicates whether each vehicle was an auto, motorcycle, small truck, or large truck. A small truck was considered to be a single-unit truck, a single-unit camper, or a delivery van. A large truck was a multiple-unit truck such as a tractor-trailer, a car or truck towing a boat or trailer, or a bus.

10.5.3 Analyses

Three analyses have been conducted regarding trucks at roundabouts. The first examined move-up times to estimate truck PCEs. The second looked at the entry capacity equation to see how the percentage of trucks affected its calibration. The third examined the impact of facility geometry on truck speed. These studies have been conducted on the basis of data from two of the roundabouts studied in *NCHRP Report 572*: the single-lane roundabout in Lothian, MD, and the double-lane roundabout in Brattleboro, VT. These two were examined most intensely because they had the highest truck flow rates.

Truck PCE Values from Move-Up Times

The two-lane roundabout on US-9 in Brattleboro, VT, was used to study move-up times. An aerial view of the roundabout is shown in Exhibit 89.

Since the roundabout is adjacent to I-91 and on major routes into New England, it is heavily loaded and sees high truck percentages, especially on the east-, south-, and westbound approaches. This facility was selected for the analysis because it has the highest truck percentages, ranging up to almost 50% during short periods of time.

Among the three approaches, nearly 20,000 events were recorded for vehicles passing through the roundabout. The events include arrival into first position on the approach, entry into the roundabout, exit from the roundabout, and passage in front of the entry point (by vehicles on the circulating roadway). Each event has a time-stamp, a lane designation, and a vehicle type.

Exhibit 89. Multilane roundabout in Brattleboro, Vermont.

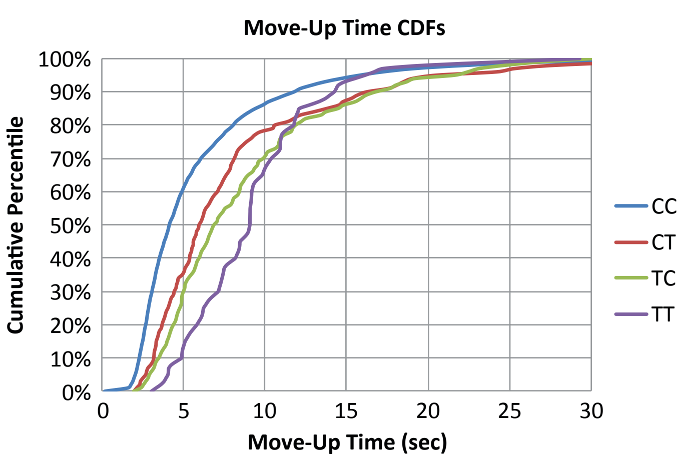
Source: North Carolina State University.

For the move-up time analysis, the events representing arrival into first position in the right-hand lane were studied. Headways were computed between successive vehicles. The headways were classified into four groups: (1) cars-following-cars, (2) cars-following-trucks, (3) trucks-following-cars, and (4) trucks-following-trucks. The inverse of these headways is the instantaneous saturation flow rate. The inverse of the low-percentile headways gives a sense of the maximum flow rate that is possible. Variations in that flow rate with the percentage of trucks give a sense of how trucks affect the maximum capacity (i.e., the input flow rate on the approach when the circulating flow rate is zero). The variation in these maximum input flow rates gives a sense of the truck PCEs.

Exhibit 90 presents the cumulative distributions (CDFs) for the four types of event pairs that were considered. The CDF labeled CC indicates a car following a car, CT indicates a truck following a car, TC indicates a car following a truck, and TT indicates a truck following a truck. There are 3156 observations of CC headways, 348 TC headways, 342 CT headways, and 41 TT headways.

At the low percentiles, these headways represent the smallest intervals at which vehicles were willing to follow one another. For the cars following cars, this ranges down to 1.6 seconds; for the trucks following trucks, about 3.0 seconds. If these headways were sustainable, this would imply a car-only capacity of 2241 veh/hr and a truck-only capacity of 1835 veh/hr. However,

Exhibit 90. Move-up time distributions for right-hand lanes of roundabout, Brattleboro, Vermont.



these headways are not sustainable, as the diagram suggests. If they were, the CDFs would be vertical at those values.

In terms of general trends, it is clear that the CC headways are generally smaller than the TC, CT, or TT headways. Moreover, the TT headways are the largest, and the CT and TC headways are in-between.

An examination of the ratios among these headways (and their implicit flow rates) shows that the one between the car-to-car and truck-to-truck flow rate remains very stable at about 2.0 across a wide spectrum of the distribution. Hence, it seems reasonable to assume that the truck PCE value is about 2.0, as portrayed presently in the HCM. The ratio of the CC flow rates to the TC flow rates is about 1.2, and the ratio of the CC flow rates to the CT flow rates is about 1.5. Hence, depending upon the mix of the traffic stream, the PCE for trucks could range from 1.2 to 2.0. If the traffic stream involved 50% trucks (obviously a high value) and the sequence consistently alternated between cars and trucks, then the ratio of the car-only flow rate to the mixed flow rate would be about 1.25 and the truck PCE would be about 2.0.

Exhibit 91 provides some insight into how the maximum entry declines with increases in the percentage of trucks. The highest rates are near 1400 veh/hr/lane at near 0% trucks, declining to about 200 veh/hr/lane for 80% trucks.

The upper bound of these values is an indication of the effect that the truck percentage has on the maximum entry flow. If the entry flow rate is extrapolated to about 1400 veh/hr when the truck percentage is 0% based on Exhibit 91 and the maximum entry rate is about 1300 veh/hr for 5% trucks, then the PCE value at that flow rate is 2.54. At the flow rate involving 50% trucks, the PCE value is 3.67. While these numbers are different from those presented before (and higher), it is clear that the percentage of trucks has an impact on the capacity relationship.

Capacity Equation Analysis

This second analysis focuses on fitting the relationship between entry flow rate and circulating flow rate. Again, the Brattleboro roundabout is used. The relationship has been studied for both the left- and right-hand lanes of the approaches.

It is assumed that the relationship between the entry capacity and the circulating flow fits the functional form presented by the HCM (see Equation 79); hence, log-linear regression can be used to obtain estimates of the coefficients involved. Specifically, this means that

$$c_{entry} = c_o * e^{-\beta * v_{conflicting}} \quad \text{Equation 80}$$

Exhibit 91. Entry flow rates, right-hand lane, Brattleboro roundabout.

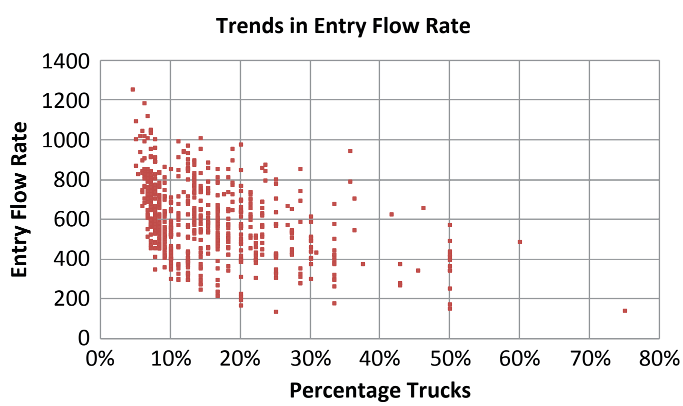


Exhibit 92. Entry capacity regression results for the multilane roundabout in Brattleboro, Vermont.

		Coefficients			t-Statistics		
%Trucks	Const	Circ	Exit	R2	Const	Circ	Exit
0%	1374	-0.76558	0.009219	0.832428	372.7105	-41.5053	0.484218
1-10%	1190	-0.53551	0.027035	0.545303	281.4225	-17.4901	1.19563
11%-20%	1258	-0.83072	0.007844	0.829712	310.4256	-34.4693	0.348901
21% +	1056	-0.68267	-0.02101	0.770002	181.3466	-20.725	-0.51598

and the values for $\ln(c_0)$ and β can be found via log-linear regression based on the following equation:

$$\ln(c_{entry}) = \ln(c_0) - \beta * v_{conflicting} \qquad \text{Equation 81}$$

This analysis has been conducted for the right-hand lane of the approaches. (The left-hand lane has also been examined, but the regression results have very low R^2 values so the analysis has not been carried further.)

To conduct the analysis, the data were processed to obtain combinations of circulating flow, entering flow (in the right-hand lane) and percent trucks (on the entry leg). Sequences of 50 vehicle events were used, with an overlap of 10 events. This is equivalent to computing moving averages. The results were then binned on the basis of the truck percentage, and regression analyses were conducted. The binned data were sorted in ascending order based on the circulating flow, and the 95th-percentile values for the circulating flow and entry flow were estimated based on sequential sets of 20 observations stepping every 10. This is equivalent to creating a moving bin and computing the 95th percentile for each realization of the bin. While it does involve using the individual observations multiple times, it helps to smooth out the random variations in the data.

The results of the regression analyses are as shown in Exhibit 92. First, it is clear that the maximum entry flow does decline as the percentage of trucks increases. (This is shown by the "Const" value.) The maximum flow value is 1,374 for 0% trucks and declines to 1,056 for 21% or more trucks. Second, the coefficient for the circulating flow remains relatively constant at about –0.7 (which happens to be the value presently shown in the HCM because the flow rates used in the regression were in thousands). Third, the *t*-statistics for both the constant and the circulating flow are consistently large, meaning that the intercept should not be zero and the coefficient for the circulating flow is statistically significant and different from zero. Fourth, even though the exiting flow rate has been considered in the analysis, its *t*-statistic is always small, which means that the exiting flow rate does not have a significant effect on the capacity of the right-hand lane.

The conclusions to draw from this analysis are threefold. First, a PCE of 2.0 for trucks is appropriate and can be applied to the circulating and entering flows in order to convert the intercept value from mixed flow rates to car-only rates and vice versa. Second, the coefficient pertaining to the circulating flow rate appears to be unaffected by the percentage of trucks in the circulating stream, so no PCE adjustment should be applied to that flow rate when computing capacity values. Third, the exiting flow rate does not seem to have an effect on entry capacity, so it can be ignored.

The finding for truck PCEs at roundabouts is that the current HCM value of 2.0 is affirmed for use. However, the field data suggest that it should only be applied to adjust the intercept of the capacity equation, not the coefficient in the exponent term.

SECTION 11

Conclusions and Recommendations

This section presents the conclusions and recommendations from NCFRP Project 41.

11.1 Conclusions

This research project reached the following conclusions regarding better incorporating trucks into *Highway Capacity Manua*l (HCM) analysis.

- **Literature Review:**
  - Most countries use passenger car equivalents (PCEs) like the U.S. HCM to convert trucks in the traffic stream into the equivalent number of passenger cars before computing capacity and speed. China, Indonesia, Singapore, Thailand, and Canada subdivide trucks into three or four subtypes (unlike the United States, which uses only a single truck category).
  - The literature identified truck weight-to-horsepower ratio as a significant factor for affecting freeway performance on extended grades. Length was identified as a possible factor affecting truck PCEs on level terrain. Position in queue was identified as a significant factor affecting saturation flow rates on signalized intersection approaches.
  - Previous research into truck level of service (LOS) from the point of view of truck drivers identified several physical attributes of the facility that affect their perceived quality of service. These include the quality of the ride and ease of driving (pavement smoothness, fewer maneuvers required, and ease of maneuvers). This research consequently recommended that speed variance and pavement quality be used as measures of truck LOS on freeways and urban streets. For urban streets, additional LOS measures were also identified: ease of turning maneuvers and traffic density.
- **Public Agency Perspectives:**
  - The majority of public agencies interviewed use HCM methods to evaluate highway performance. The second most commonly used tool is microsimulation, followed by FHWA's Freight Analysis Framework (which uses the area-wide planning method from the 2000 edition of the HCM).
  - There is a strong preference among the agencies interviewed for a truck LOS methodology that they can use for ranking goods-movement investments and evaluating general highway capacity investments.
  - The agencies believe that truck LOS should be sensitive to travel time reliability, traffic congestion, and average speed.
- **Shipper and Carrier Perspectives:**
  - The interviews and survey of shippers and carriers found that freight decisionmaking is complex and often varies by establishment. In addition, the criticality of travel time and on-time delivery varies by a factor of 10 depending on the cost of the material being hauled and the distance hauled (travel time). Lower-valued goods hauled for longer distances (or times) have the lowest value of time.

- In general, travel time, cost, and reliability (on-time performance) are the key determinants of route selection. Local laws, long-term contracts between shippers and receivers, the type of goods being shipped, transportation costs and travel times, and logistics supply chains all impact the relative importance of these attributes in decisionmaking of shippers, receivers, and carriers.

- **Vehicle Classification System:**
  - The FHWA axle- and trailer-based vehicle classification system is the appropriate foundation for classifying trucks for the purpose of highway capacity analyses. While there are still significant variations in vehicle performance within each of the 13 FHWA vehicle classes, the FHWA system is greatly superior to the current 4-class system in the HCM (i.e., passenger cars, buses, RVs, and trucks). The FHWA system also has the significant advantage of being a nationally established consistent system for which weigh-in-motion data is already readily available.
  - The 13 FHWA vehicle classes are more than is really needed for HCM analyses, given that many of the classes account for very small percentages of the vehicle fleet. Consequently, it was concluded that the 13 FHWA vehicle classes should be consolidated into the following 5 HCM classes for the purposes of HCM analyses:
    1. Passenger Vehicles (FHWA Classes 1, 2, and 3);
    2. Buses (FHWA Class 4);
    3. Recreational Vehicles (RVs) (a subcategory within FHWA Class 5);
    4. Single-Unit Trucks (FHWA Classes 5–7); and
    5. Semitrailer Trucks (FHWA Classes 8–13).
- **Impacts of Trucks on Other Modes:**
  - The current HCM method for basic freeway segments (Chapter 11) of converting trucks into passenger car equivalents is deficient for predicting automobile speeds and truck speeds on extended upgrades under moderate to high flow conditions (3% or greater grades extending over 1 mile, with 5% or more trucks in the traffic stream, under volume/capacity ratios in excess of 0.30).
  - The current HCM method for estimating speeds for urban street segments (Chapter 17) is insensitive to truck or grade effects. This becomes a significant defect for extended upgrades (3% or more extending over 1 mile).
  - The current HCM default PCE value of 2.0 for all trucks in roundabouts (Chapter 21) appears to be appropriate.
  - The HCM's signalized intersection method (Chapter 18) significantly underestimates the impacts of trucks on saturation flow rates for upgrades in excess of 2%. The relative mix of semitrailer and single-unit trucks had a comparatively minor effect on saturation flow rates (the total percent trucks and grade had significantly greater effects).
- **Impacts of Other Modes on Trucks (Truck LOS):**
  - Truck LOS should take into account average truck travel times, truck travel time reliability, and cost (where tolls are involved) as well as the truck friendliness of the facility (its ability to safely and legally accommodate all legal vehicles and loads, with as few at-grade railroad crossings as feasible).

11.2 Recommendations

This research produced the following recommendations for better incorporating truck analysis into the HCM.

- **Vehicle Classification System:**
  - The 13 FHWA vehicle classes are more than is really needed for HCM analyses, given that many of the classes account for very small percentages of the vehicle fleet. The current

single-truck class in the HCM, however, is inadequate to account for the significant performance differences between single-unit trucks and semitrailer truck combinations. Consequently, it is recommended that trucks in the HCM be split into two vehicle classes, resulting in the following five HCM classes for the purposes of HCM analyses:

1. Passenger Vehicles (FHWA Classes 1, 2, and 3);
2. Buses (FHWA Class 4);
3. RVs (a subcategory within FHWA Class 5);
4. Single-Unit Trucks (FHWA Classes 5–7, excluding RVs); and
5. Semitrailer Trucks (FHWA Classes 8–13).

- **Impacts of Trucks on Other Modes:**
  – NCFRP Project 41 was able to make significant advances in developing an improved HCM method for estimating automobile and truck speeds on extended upgrades (see Section 8). A preliminary set of equations was developed for predicting speeds. Further research on these speed prediction methods is given in Appendix D. However, as described under "further research," further testing and validation is required before these methods can be recommended to replace the existing HCM Chapter 11 methodology.
  – The project also made significant progress on developing a truck- and grade-sensitive speed estimation method for arterial street segments (HCM Chapter 17) (see Section 9). However, further research will be needed to integrate the new method with the current HCM Chapter 17 method.
  – For signalized intersections (HCM Chapter 18), is recommended that the current heavy-vehicle and grade adjustment factors in the saturation flow equation be replaced with a single combined factor that better accounts for the synergistic effects of heavy vehicles on signalized intersection approaches with steep upgrades (in excess of 2%).
- **Impacts of Other Modes on Trucks:**
  – This research developed a recommended truck LOS model based on mean speed, travel time reliability, and added cost associated with tolls (see Section 6).

11.3 Recommended HCM Implementation Plan

This section provides a recommended HCM Implementation Plan for moving the results of the research into practice.

11.3.1 Incorporation into NCHRP Project 3-115 (HCM Update)

This research developed, described, and demonstrated new methods for evaluating the effects of highway and street facility performance on trucks (truck LOS) and the effects of trucks on other modes (truck PCEs).

- Appendix F provides the recommended edits to the 2010 edition of the *Highway Capacity Manual.* A computational engine was developed for the truck LOS model.
- Appendix E provides a User's Guide for the computational engine.

Together, these two products—Appendixes E and F—will facilitate the incorporation of the results of this research into the next update of the HCM, currently being accomplished under NCHRP Project 3-115.

Other aspects of the NCFRP Project 41 research (Sections 8, 9, and 10 related to truck speeds and PCEs on extended grades) would involve major changes to current HCM procedures and therefore must wait until further research can be conducted to better define and validate the new methods.

11.3.2 Expected Audience/Market for Research Product

The expected audience for the research product is the transportation engineering and planning professional community involved in the planning and prioritization of all highway and street improvements. This includes private consultants or employees working for state DOTs, MPOs, cities, and counties. FHWA will also be a user of the products in their role as evaluators or advisors to the development of transportation plans and investment programs.

11.3.3 Possible Impediments to Successful Implementation

Lack of awareness and knowledge of the new truck analysis methods is the greatest potential impediment to the successful adoption and implementation of the research product. A secondary potential impediment would be the lack of software to facilitate application of the recommended truck analysis procedures.

11.3.4 Likely Institutional Leaders in Application

The likely institutional leader for gaining acceptance of the new methodology for evaluating truck LOS in U.S. practice is FHWA. By adopting the approach as a recommended or required analytical approach for analyses conducted in support of federal funding applications for highway improvement projects, FHWA would go a long way toward securing national acceptance of the concept. State DOTs and MPOs can be leaders in adopting the new method. The Institute of Transportation Engineers (ITE) can promote the new method through training classes.

11.3.5 Activities for Successful Implementation

Inclusion of the new methodology in future editions of the HCM would go a long way to successfully implementing the results of this research. However, just being in the HCM does not ensure actual use of the method.

NCFRP Project 41 conducted two workshops with public agency personnel to acquaint a core group of professionals with the new truck LOS analysis methods and computational engines implementing the new methods. NCFRP Project 41 also developed a computational engine for the truck LOS model to facilitate the development of commercial software to implement the methods. (The computational engine, with its limited user interface, will not replace the need for some other commercially oriented product to implement the new HCM truck analysis methods.) The computational engine illustrates for software developers how they might program and match the recommended methodology with their programs.

Together, the HCM 2010 updates, the computational engine, and the two workshops (already conducted) will greatly facilitate increased awareness of the products of this research. Additional steps that can be taken in the future include the following:

- Showcasing the NCFRP Project 41 products at one of the regular FHWA "Talking Freight" webinars (currently included in Task 11 of NCFRP Project 41) will greatly increase awareness of the new truck analysis methodology and new HCM chapter.
- Additional workshops on truck LOS after the publication of the HCM 2010 updates (not included within the current scope for this research project) would greatly increase awareness of the truck LOS model.
- A series of papers and presentations prepared by key research team leaders for presentation at ITE and TRB annual meetings will help generate interest by agencies in the method.

11.3.6 Criteria for Determining Progress and Success

The key criteria of success will be the adoption of the analysis methods developed in this project by public agencies, inclusion of the methodologies in FHWA guidance documents and the *Highway Capacity Manual,* adoption of truck LOS standards by state DOTs and other transportation agencies, and inclusion of the new methods in commercially available highway capacity analysis software.

11.4 Applicability of Results to Practice

This research resulted in methodologies and a computational engine for predicting the impacts of highway and street investments on truck LOS, taking into account the relative economic importance to the community. The methodologies will enable agencies to take into consideration truck freight movement effects in their prioritization of transportation improvements.

11.5 Recommendations for Further Research

While both the arterial segment and freeway basic segment speed models will require further research before they can be implemented in the HCM, the freeway basic segment model appears to be the most promising topic to follow up on. The underestimation of the deleterious effects on average speeds of extended freeway upgrades is a significant problem when performing economic analyses of the need for freeway truck climbing lanes. Further research to better define and validate the NCFRP Project 41 freeway speed model for extended grades will significantly improve the investment decisionmaking of state DOTs and other public agencies involved in planning and programming freeway improvements.

11.5.1 Need for Further Research

The PCE research portion of this project revealed a serious flaw in the current HCM approach for evaluating long, steep grades (upgrades of 4% as short as 1 mile in length). The current HCM approach converts trucks to PCEs and then uses the passenger car speed flow curve to estimate average speed and density of vehicles, which is used for LOS computations.

The research found that there are actually two speed-flow curves on long, steep grades, one for passenger cars and one for trucks. At light flows passenger cars can pass the slower trucks and the facility actually has two speeds, one for trucks and one for passenger cars. As flows or the percent of trucks increase, the two-vehicle class phenomenon breaks down and all vehicles travel at the speed of the trucks (this breakdown happens at moderate truck percentages and volumes, long before the HCM estimated capacity is reached).

The effect of this flaw in the current HCM approach is that the need for and the benefits of truck climbing lanes on long, steep grades are significantly underestimated by any analysis employing the 2010 HCM and its earlier editions.

The effect becomes evident, especially at-and-near capacity, whenever the grade is steep enough (even for short distances) to force a drop in the truck speeds. It has a major implication for computing the benefit of separating the trucks from the rest of the traffic stream. The effect is significant enough that the current density-based automobile LOS methodology in the HCM for freeway grades may need to be replaced by one that is based on automobile and truck delay.

11.5.2 Objectives of Further Research

The objectives of the further research would be the development and calibration of a new two-vehicle class (passenger cars and heavy vehicles) HCM method evaluating the capacity and performance (speed and density) of freeway segments on long, steep grades. This method will require

- Creation of heavy-vehicle speed flow curves (truck, RVs, and bus, as appropriate) for use on long, steep freeway upgrades;
- Creation of a methodology for quantifying the impact on passenger car speeds of different mixes and volumes of heavy vehicles on long, steep upgrades that takes into account possible countermeasures such as truck lane restrictions and truck climbing lanes; and
- Creation of a procedure combining the separate passenger car and truck speeds into a measure of overall facility performance (such as mean speed and density).

11.5.3 Approach for Further Research

The freeway simulation test bed already developed and calibrated under the current research would be employed to develop the new HCM method. In addition, field testing would be conducted using data sets already collected for this and other projects. The field data set testing will verify the method's ability to match actual facility performance. The final report and draft chapter produced by this project would then be expanded to incorporate the results of the additional research to develop a two-vehicle class procedure for evaluating the performance of freeway facilities with long steep grades.

The objectives of the additional research would be accomplished with the following tasks:

- **Simulation Experiments:** Focus on a richer set of conditions so that HCM models can be developed that predict automobile and heavy-vehicle speeds and densities for a variety of upgrades and grade lengths, taking into account interactions between the vehicle types for a comprehensive set of potential field conditions. This task includes preparing the simulation models for the broader set of tests, conducting the simulations, and analyzing the results.
- **Model Development:** Refine and extend the limited set of HCM predictive models for passenger car and truck speed and density that came out of the research to date. Determine the interaction and interference effects between vehicle types. Develop a method to predict combined average speed and density. Compare the new HCM predictive models with the original simulation results and assess their performance.
- **Case Studies:** Examine a larger set of field settings using data sets already available to the research team where there are significant grades, truck percentages, and so forth so that the predictions of the models can be checked, validated, and further refined. This task includes assembling the data, preparing the models, and conducting the analyses.
- **Final Report**: Expand the final report to describe and present the findings from the experiments and case studies. This task includes preparing the report.
- **Draft HCM Materials:** Expand the draft truck analysis chapter for the HCM to include the new methodology for evaluating truck and passenger car speeds and densities on long steep upgrades and predicting the effects of truck lane restrictions and truck climbing lanes on freeway segment performance. Advise the HCM 2010 Update contractor on inserting the new material into the body of the HCM.

References

AASHTO. (2011). *A Policy on Geometric Design of Highways and Streets, 6th Edition.* Washington, DC: American Association of State Highway and Transportation Officials.

Abdelgawad, H., Abdulai, B., Amirjamshidi, G., Wahba, M., Woudsma, C., and Roorda, M. (2010). Simulation of Exclusive Truck Facilities on Urban Freeways, *Compendium of Papers 89th Annual Meeting TRB* (Paper 10-2096). Transportation Research Board, the National Academies, Washington, DC.

Aggarwal, P. (2011). Passenger Car Unit Value for Trucks Using Fuzzy Model. *Proceedings of the World Congress on Engineering.* London, UK.

Ahanotu, D. N. (1999). *Heavy-Duty Vehicle Weight And Horsepower Distributions: Measurement Of Class-Specific Temporal And Spatial Variability (Doctoral Thesis).* Atlanta, GA: Georgia Institute of Technology.

Alam, M., and Rajamanickam, G. (2007). *Development of Truck Payload Equivalent Factors.* Washington, D.C.: Federal Highway Administration.

Austroads. (n.d.). *Guide to Traffic Management, Part 3: Traffic Studies and Analysis.* Retrieved September 2011, from www.onlinepublications.austroads.com.au/collections/agtm/guides.

Bang, K.-L., and Heshen, A. (2000). Development of Capacity Guidelines for Road Links and Intersections for Henan and Hebei Provinces, PRC. *Transportation Research Circular E-C018: Fourth International Symposium on Highway Capacity* (pp. 287–298). Transportation Research Board, National Research Council, Washington, DC.

Benekohal, R. F., and Girianna, M. (2003).Technologies for Truck Classification and Methodologies for Estimating Truck Vehicle Miles Traveled, *Transportation Research Record 1855: Transportation Data Research* (pp. 1–13). Transportation Research Board, the National Academies, Washington, DC.

Boltze, M. (2006). Recent Developments in Germany Related to Highway Capacity and Quality of Service. *5th International Symposium on Highway Capacity and Quality of Service.* Japan Society of Traffic Engineers.

Brilon, W., and Bressler, A. (2004).Traffic Flow on Freeway Upgrades, *Transportation Research Record 1883: Traffic Flow Theory and Highway Capacity and Quality of Service 2004* (pp. 112–121). Transportation Research Board, the National Academies, Washington, DC.

Burke, M. (2012). SR 7 Vehicle Classification Data for SR 7 at Hudson River. New York, USA: New York State Department of Transportation.

Burr, I. (1942). Cumulative Frequency Functions, *Annals of Mathematical Statistics, 13,* 215–232.

Caltrans. (n.d.). *Traffic Counts—2009 AADT.* Retrieved 2011, from California Department of Transportation: www.dot.ca.gov/hq/traffops/saferesr/trafdata/index.htm.

Cambridge Systematics. (n.d.). *Best Practices for MPO Freight Planning.* Retrieved September 17, 2012, from Capital Area Metropolitan Plannon Organization: www.campo-nc.us/2009-conference-slides/Presentations/PDFs/B.2-Ahanotu-Best_Practices_MPO_Freight_Planning_v2.pdf.

Cambridge Systematics. (in process). *PANYNJ Cross Harbor Freight Movement EIS.* Jersey City, NJ: The Port Authority of New York and New Jersey.

Cambridge Systematics. (2006). *Minnesota Truck Size and Weight Project.* Minneapolis, MN: Minnesota Department of Transportation.

Canadian Institute of Transportation Engineers. (2008). *Capacity Guide for Signalized Intersections.* Canadian Institute of Transportation Engineers.

Cottrell, B., and Kweon, Y.-J. (2009). *Review of the Virginia DOT's Truck Weight Data Plan for the MEPDG.* Charlottesville, VA: Virginia Center for Transportation Innovation and Research.

Cunha, C. L., and Setti, J. R. (2011). Truck Equivalence Factors for Divided, Multilane Highways in Brazil. *Procedia—Social and Behavioral Sciences, Volume 16, 6th International Symposium on Highway Capacity and Quality of Service,* (pp. 248–258). Stockholm, Sweden.

Demarchi, S. H., and Setti, J. R. (2003). Limitations of Passenger-Car Equivalent Derivation for Traffic Streams with More Than One Truck Type. *Transportation Research Record 1852: Traffic Flow Theory and Highway Capacity 2003,* (pp. 96–104); Transportation Research Board, the National Academies, Washington, DC.

Danielis, R., Marcucci, E., and Rotaris, L. (2005). Logistics Managers' Stated Preference for Freight Service Attributes. *Transportation Research Part E: Logistics and Transportation Review,* 201–215.

Department of Transport, Highways Agency. (n.d.). *Design Manual for Roads and Bridges, Volume 5: Assessment and Preparation of Road Schemes.* Retrieved 2011 from www.dft.gov.uk/ha/standards/index.htm.

Diefenderfer, B. (2008). Presentation. *TRB MEPDG Workshop.* Charlottesville, VA: Virginia Center for Transportation Innovation and Research.

Dowling Associates. (2012). *Users Guide for California Motor Vehicle Stick, Travel, and Fuel Forecast Modeling System (MVSTAFF).* Sacramento: California Department of Transportation.

Dowling, R., Reinke, D., Flannery, A., Ryus, P., Vandehey, M., Petritsch, T., et al. (2008). *NCHRP Report 616: Multimodal Level of Service Analysis for Urban Streets.* Transportation Research Board, the National Academies, Washington, DC.

Elefteriadou, L., Arguea, A., Kondyli, A., and Heaslip, K. (2007). *Impact of Trucks on Arterial LOS and Freeway Work Zones Capacity (Part B).* Gainesville, FL: Transportation Research Center, University of Florida.

Elkins, L., and Higgins, C. (2008). *Development of Truck Axle Spectra from Oregon Weigh-in-Motion Data for Use in Pavement Design and Analysis.* Washington, DC: Federal Highway Administration.

Fan, H. S. (1990). Passenger Car Equivalents for Vehicles on Singapore Expressways. *Transportation Research Part A 24A(1),* 391–396.

Federal Register. (2013, February). *Federal Register, 78*(25), 8686–8689.

FGSV. (2001). *HBS: Handbuch für die Bemessung von Straßenverkehrsanlagen.* Cologne: Forschungsgesellschaft für Straßen- und Verkehrswesen e.V.

FHWA. (n.d.). *Freight Management and Operations.* Retrieved September 17, 2012, from www.ops.fhwa.dot.gov/freight/.

FHWA. (n.d.). *National Highway System: Federal Highway Administration.* Retrieved September 17, 2012, from www.fhwa.dot.gov/planning/national_highway_system/.

FHWA. (n.d.) *Releases and Speeches: Federal Highway Administration.* Retrieved September 17, 2012, from www.dot.gov/affairs/2012/dot9812.html.

FHWA. (n.d.) *Truck Size and Weight: Federal Highway Administration.* Retrieved September 17, 2012, from ops.fhwa.dot.gov/freight/sw/index.htm.

FHWA. (1989). *FHWA Functional Classification Guidelines.* Washington, D.C.: Federal Highway Administration.

FHWA. (2000). *Roundabouts: An Informational Guide.* Washington, DC: Federal Highway Administration.

FHWA. (2001). *Analysis of the Vehicle Inventory and Use Survey for Trucks with Five Axles or More.* Washington, D.C.: Federal Highway Administration.

FHWA. (2001, May 1). *Traffic Monitoring Guide.* Retrieved September 14, 2012, from Office of Highway Policy Information: www.fhwa.dot.gov/ohim/tmguide/tmg4.htm.

FHWA. (2004). *Federal Size Regulations for Commercial Motor Vehicles.* Washington, DC: Federal Highway Administration, Office of Freight Management and Operations.

FHWA. (2007). *Guidelines for Applying CORSIM Microsimulation Modeling Software.* Washington, DC: Federal Highway Administration.

FHWA. (2009). *Freight Analysis Framework,Version 2.2.* Washington, DC: Federal Highway Administration, Office of Freight Management and Operations.

FHWA. (2010). *Freight Facts and Figures 2010* (Vols. FHWA-HOP-10-058). Washington, DC: Federal Highway Administration.

FHWA. (2010). *Major Truck Routes on the National Highway System: 2007.* Office of Freight Management and Operations, Federal Highway Administration. Washington, DC.

FHWA. (2012). *Freight Analysis Framework 3 User Guide.* Washington, DC: Federal Highway Administration.

FHWA. (2012). *Highway Performance Monitoring System Field Manual.* Washington, D.C.: Federal Highway Administration.

FHWA. (2012, August 31). *Vehicle Travel Information System.* Retrieved from Federal Highway Administration, Policy Information: www.fhwa.dot.gov/ohim/ohimvtis.cfm.

FHWA. (2013, June 26). *National Highway System.* Retrieved August 11, 2013, from www.fhwa.dot.gov/planning/national_highway_system/.

FHWA. (2013, December 3). *Performance Measurement.* Retrieved December 8, 2013, from Freight Management and Operations: www.ops.fhwa.dot.gov/freight/freight_analysis/perform_meas/vpds/npmrdsfaqs.htm.

Fowkes, A. S., Firmin, P. E., Tweddle, G. and Whiteing, A.E. (2004). How Highly Does the Freight Transport Industry Value Journey Time Reliability—and for What Reasons? *International Journal of Logistics 7 (1),* 33–43.

Fwa, Ang, and Goh. (1996). Characteristics of Truck Traffic in Singapore, *Journal of Advanced Transportation.*

Geistefeldt, J. (2009). Estimation of Passenger Car Equivalents Based on Capacity Variability. *Transportation Research Record 2130: Highway Capacity and Quality of Service 2009,* (pp. 1–6); Transportation Research Board, the National Academies, Washington, DC.

Harwood, D. W., Torbic, D. J., Richard, K. R., Glauz, W. D., and Elefeteriadou, L. (2003). *NCHRP Report 505: Review of Truck Characteristics as Factors in Roadway Design.* Transportation Research Board, the National Academies, Washington, DC.

Hausrath Economics Group and Cambridge Systematics, Inc. (2004). *Task 11 Working Paper: A Land Use Strategy to Support Regional Goods Movement in the Bay Area.* Metropolitan Transportation Commission.

Hostovsky, C., and Hall, F. (2003).Freeway Quality of Service: Perceptions from Tractor-Trailer Drivers. *Transportation Research Record 1852: Traffic Flow Theory and Highway Capacity 2003,* (pp. 19–25); Transportation Research Board, the National Academies, Washington, DC.

Indian Central Road Research Institute. (1988). *Capacity of Roads in Urban Areas.* New Delhi: Indian Ministry of Surface Transport.

Indian Roads Congress. (1994). *Guidelines for the Design of At-Grade Intersections in Rural and Urban Areas* (Vol. Special Publication 41). New Delhi.

Indonesian Directorate General of Highways. (1993). *Indonesian Highway Capacity Manual, Part I Urban Roads.* Indonesian Ministry of Public Works.

Indonesian Directorate General of Highways. (1995). *Indonesian Highway Capacity Manual, Part II Interurban Roads.* Indonesian Ministry of Public Works.

ITE. (2009). *Traffic Engineering Handbook, 6th Edition.* (W. H. Kraft, Ed.) Washington, DC: Institute of Transportation Engineers.

Kittelson and Associates, Inc. (2012). SHRP2 Project L08 Final Report: Incorporation of Travel Time Reliability into the Highway Capacity Manual. Prepublication Draft for a SHRP 2 Research Report. Transportation Research Board, the National Academies, Washington, DC.

Kittelson, W., Courage, K., Kyte, M., List, G., Roess, R., and Sampson, W. M. (2003). *NCHRP: Highway Capacity Manual Applications Guidebook,* retrieved 2013*:* www.hcmguide.com/index.htm. Transportation Research Board, the National Academies, Washington, DC.

Ko, B., Washburn, S., and McLeod, D. (2009). Performance Measures for Truck Level of Service, An Exploratory Survey Analysis. *Transportation Research Record 2130: Highway Capacity and Quality of Service 2009,* (pp. 120–128); Transportation Research Board, the National Academies, Washington, DC.

Komanduri, A., Musti, S., and Proussaloglou, K. (2012). Modeling Values of Time to Support Freight Decision-Making: Results from a Stated Preference Survey in New York, Paper presented at 2012 Transport Chicago Conference, June 1, 2012 (10 pp.).

Kweon, Y.-J., and Cottrell, B. J. (2011). Analysis of Weigh-in-Motion Data for Truck Weight Grouping for Pavement Design, *Transportation Research Record 2256: Urban and Traffic Data Systems* (pp. 169–178); Transportation Research Board, the National Academies, Washington, DC.

Lane, J. (2008, February 22). *Briefing to American Association of State Highway and Transportation Officials.* Retrieved September 14, 2012, from Portland State University College of Urban and Public Affairs: www.pdx.edu/prc/gsearch/officials%20aashto.

Maryland SHA. (2012, June 28). *Description of Classes.* Retrieved September 14, 2012, from Maryland State Highway Administration: www.marylandroads.com/oppen/Vehicle_Class.pdf.

Mathetharan, V. (1997). *Determination of Highway Capacity on Uninterrupted Flow Highway, AIT Thesis, No. TE-96-4.* Thailand: Asian Institute of Technology.

McCall, B., and Vodrazka, W. J. (1997). *State's Successful Practices Weigh-in-Motion Handbook.* Washington, DC: Federal Highway Administration.

Metro. (2010). *Regional Freight Plan 2035.* Portland: Metro.

Metropolitan Transportation Commission. (2004). *Regional Goods Movement Study for the San Francisco Bay Area.* Oakland: Metropolitan Transportation Commission.

Middleton, D. (2006). *Strategies for Separating Trucks From Passenger Vehicles: Final Report.* Texas Transportation Institute.

Minh, C., and Sano, K. (2003). Analysis of Motorcycle Effects to Saturation Flow Rate at Signalized Intersection in Developing Countries. *Journal of the Eastern Asia Society for Transportation Studies, Volume 5,* 1211–1222.

Minnesota DOT. (2004). *Advanced CORSIM Training Manual.* Minneapolis, MN: Minnesota Department of Transportation.

Monsere, C., Mecit, C., and Nichols, A. (2011). *Explanatory Methods for Truck Re-Identification in a Statewide Network Based on Axle Weight and Axle Spacing Data to Enhance Freight Metrics.* Portland, OR: Oregon Transportation Research and Education Consortium.

Monsere, C., and Nichols, A. (2008). Building a WIM Data Archive for Improved Modeling, Design, and Rating. Presented at *North American Travel Monitoring Exhibition and Conference.*

Morikawa, T., Miwa, T., and Sun, X. (2011). The Impact of Automated Truck Lanes on Intercity Expressways: A Study Using Hybrid Simulator. *Journal of Transportation Systems Engineering and Information Technology, 11,* 32–42.

National Surface Transportation Policy and Revenue Study Commission. (n.d.). Retrieved September 17, 2012, from transportationfortomorrow.com/.

New York DOT. (n.d.). *New York DOT: Trucks and Commercial Vehicles.* Retrieved September 17, 2012, from New York DOT: www.nyc.gov/html/dot/html/motorist/trucks.shtml.

Oregon DOT. (2009, April 6). *ODOT weigh-in-motion system clears 11 million trucks and saves industry $100 million.* Retrieved 2012, from Oregon State Department of Transportation: oregon.gov/ODOT/COMM/greenlight.shtml.

Papagiannakis, A. T., Quinley, R., and Brandt, S. R. (2008). *NCHRP Synthesis of Highway Practice 38: High Speed Weigh-in-Motion System Calibration Practices,* Transportation Research Board, the National Academies, Washington, DC.

Partha, P. P., Chandra, S., and Gangopadhaya, S. (2008). Simulation of Mixed Traffic Flow on Two-Lane Roads. *Journal of Transportation Engineering,* 361–369.

PTV Group. (n.d.). *PTV Vissim.* Retrieved December 6, 2013, from Explore PTV Group: vision-traffic.ptvgroup.com/en-us/products/ptv-vissim/.

Quinley, R. (2002). The CTWIM Suite. *North American Travel Monitoring Exhibition and Conference 2002.* Orlando, FL.

Rahman, M. M., Okura, I., and Nakamura, F. (2003). Measuring Passenger Car Equivalent (PCE) for Large Vehicles at Signalized Intersections. *Journal of the Eastern Asia Society for Transportation Studies, 5,* 1223–1233.

Rakha, H. A., Ingle, A., Hancock, K. L., and Al-Kaisy, A. F. (2007). Estimating Truck Equivalencies for Freeway Sections. *Transportation Research Record 2027: Highway Capacity and Quality of Service 2007* (pp. 73–84); Transportation Research Board, the National Academies, Washington, DC.

Rakha, H., Lucic, I., Demarchi, S., Setti, J., and Aerde, M. (2001). Vehicle Dynamics Model for Predicting Maximum Truck Acceleration Levels. *ASCE Journal of Transportation Engineering, 127*(5), 418–425.

Ramsay, E. D., Bunker, J. M., and Troutbeck, R. (2004). Signalized Intersection Capacity Reduction of Trucks. *Proceedings of the Fourth International Conference on Traffic and Transportation Studies.* Dalian, China.

Research and Innovative Technology Administration. (n.d.). *Commodity Flow Survey.* Retrieved August 2012, from Bureau of Transportation Statistics: www.bts.gov/publications/commodity_flow_survey/.

Rhodes, S., Berndt, M., Bingham, P., Bryan, J., Cherrett, T., Plumeau, P., and Weisbrod, R. (2012). *NCFRP Report 14: Guidebook for Understanding Urban Goods Movement.* Transportation Research Board, the National Academies, Washington, DC.

Rodegerdts, L., Blogg, M., Wemple, E., Myers, E., Kyte, M., Dixon, M., et al. (2007). *NCHRP Report 572: Roundabouts in the United States.* Transportation Research Board, the National Academies, Washington, DC.

Roorda, M. J., Hain, Amirjamshidi, Cavalcante, Abdulhai, and Woudsma. (2010). Exclusive Truck Facilities in Toronto, Ontario, Canada: Analysis of Truck and Automobile Demand, *Transportation Research Record 2168: Freight Transportation Modeling, Planning, and Logistics* (pp. 114–128); Transportation Research Board, the National Academies, Washington, DC.

San Francisco MTA. (n.d.). *Trucks and Bus Restricted Streets Map.* Retrieved September 14, 2012, from San Francisco Municipal Transportation Agency: www.sfmta.com/cms/venf/truckbus.htm.

Shinghal, N., and Fowkes, A. S. (2002). Freight Mode Choice and Adaptive Stated Preferences. *Transportation Research, Part E, 38 (5),* 367–378.

Smalkoski, B., and Levinson, D. (2005). Value of Time for Commercial Vehicle Operators in Minnesota. *Journal of the Transportation Research Forum 44 (1),* 89–102.

Small, K., Noland, R., Chu, X., and Lewis, D. (1999). *NCHRP Report 431: Valuation of Travel-Time Savings and Predictability in Congested Conditions for Highway User-Cost Estimation.* Transportation Research Board, the National Academies, Washington, DC.

Stone, J. R. (2011). *Development of Traffic Data Input Resources for the Mechanistic Empirical Pavement Design Process.* Raleigh, NC: North Carolina Department of Transportation.

Stone, J., Kim, Y. R., List, G. F., Rasdorf, W., Sayyady, F., Jadoun, F., and Ramachandran, A.N. (2010). *Development of Traffic Data Input Resources for the Mechanistic Empirical Pavement Design Process.* Raleigh, NC: North Carolina Department of Transportation.

Tanaboriboon, Y., and Aryal, R. (1990). Effect of Vehicle Size on Highway Capacity in Thailand. *Journal of Transportation Engineering, Volume 116,* 658–666.

Taylor, M. A., and Susilawati. (2012). Using The Burr Distribution For Measuring Travel Time Reliability. *Proceedings of the 5th International Symposium on Transportation Network Reliability.* Hong Kong, China.

The Tioga Group. (2007). *SACOG Regional Goods Movement Study, Phase Two White Papers.* Sacramento: SACOG.

TRB. (2010). *Highway Capacity Manual 2010.* Transportation Research Board, the National Academies, Washington, DC.

U.S. Census. (n.d.). *American FactFinder.* Retrieved August 2012 from U.S. Census Bureau: factfinder2.census.gov/faces/nav/jsf/pages/index.xhtml.

U.S. Congress. (n.d.). *H.R. 7360 (97th): Surface Transportation Assistance Act of 1982.* Retrieved September 14, 2012, from govtrack.us: www.govtrack.us/congress/bills/97/hr7360.

Virginia DOT. (2008). *Annual Daily Traffic Volumes with Vehicle Classification Data on Interstate, Arterial and Primary Routes.*

Washburn, S. (2002). *Multimodal Quality of Service Part I: Truck Level of Service.* Gainesville, FL: Transportation Research Center, University of Florida.

Washburn, S., and Cruz-Casas, C. O. (2010). Impact of Trucks on Signalized Intersection Capacity. *Computer-Aided Civil and Infrastructure Engineering, 25,* 452–467.

Washburn, S., and Ko, B. (2007). *Travel Time Reliability and Truck Level of Service on the Strategic Intermodal System.* Tallahassee, FL: Florida Department of Transportation.

Webster, N. E. (1999). Simulation Study of Truck Passenger Car Equivalents (PCE) on Basic Freeway Sections. *Transportation Research B, 33, No. 5,* 323–336.

Wikipedia. (n.d.). *Filbert Street (San Francisco).* Retrieved September 13, 2012, from en.wikipedia.org/wiki/Filbert_Street_(San_Francisco).

Wikipedia. (n.d.). *List of regions of the United States.* Retrieved September 2012 from en.wikipedia.org/wiki/List_of_regions_of_the_United_States#Standard_Federal_Regions.

Woodrooffe, J., Billing, J., Middleton, D., and Sweatman, P. (2011). Canadian Truck Size and Weight Policy Development Are There Lessons for the U. S.? *Compendium of Papers 90th Annual Meeting of the Transportation Research Board* (Paper 11-3866). Transportation Research Board, the National Academies, Washington, DC.

Wordsworth, S. (2011). Identity Parade. *Traffic Technology International,* 52. June/July.

Wu, N. (1998). The Proposed New Version of German Highway Capacity Manual. *ASCE Conference Proceeding: Traffic and Transportation Studies.* American Society of Civil Engineers.

Appendixes A–F

The following appendixes are unpublished herein but can be found online at www.trb.org by searching for NCFRP Project 41:

- Appendix A: Regional Defaults for Average Shipping Distances and Times
- Appendix B: Public Agency Workshops to Evaluate Methods
- Appendix C: Surveys and Interviews
- Appendix D: Additional Thoughts on Freeway Truck Speeds
- Appendix E: Computational Engines Users Guides
- Appendix F: Draft HCM Chapter Materials

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation