# Delay and Environmental Costs of Truck Crashes

U.S. Department of Transportation
**Federal Motor Carrier Safety Administration**

**March 2013**

# FOREWORD

This report presents estimates of certain categories of costs of truck- and bus-involved crashes. Crash related costs estimated as part of this study include vehicle delay costs, emission costs, and fuel consumption costs. In addition, this report also develops improved methods for estimating property damage costs and presents the results of that improved methodology used on updated data. Finally, the report presents costs specific to crashes involving hazardous material (HM) releases. The development of each of these costs, including underlying assumptions, model framework and methodology, and data analysis, is discussed in detail.

# NOTICE

# Technical Report Documentation Page

| | | |
|---|---|---|
| 1. Report No.<br>**FMCSA-RRA-13-043** | 2. Government Accession No. | 3. Recipient's Catalog No. |
| 4. Title and Subtitle<br>**Delay and Environmental Costs of Truck Crashes** | | 5. Report Date<br>**March 2013** |
| | | 6. Performing Organization Code |
| 7. Author(s)<br>**Garrett Hagemann, Kent Hymel, Adam Klauber, Douglass B Lee, George Noel, David Pace, Catherine Taylor** | | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address<br>**USDOT/Volpe Center, Cambridge, MA** | | 10. Work Unit No. (TRAIS) |
| | | 11. Contract or Grant No. |
| 12. Sponsoring Agency Name and Address<br>**U.S. Department of Transportation**<br>**Federal Motor Carrier Safety Administration**<br>**Office of Analysis, Research, and Technology**<br>**1200 New Jersey Ave., SE**<br>**Washington, DC 20590** | | 13. Type of Report and Period Covered<br>**Final Report** |
| | | 14. Sponsoring Agency Code<br>**FMCSA** |
| 15. Supplementary Notes<br>**Contracting Officer's Technical Representative: Michael Johnsen** | | |

16. Abstract

**This report presents estimates of certain categories of costs of truck- and bus-involved crashes. Crash related costs estimated as part of this study include vehicle delay costs, emission costs, and fuel consumption costs. In addition, this report also develops improved methods for estimating property damage costs and presents the results of that improved methodology used on updated data. Finally, the report presents costs specific to crashes involving hazardous material (HM) releases. The development of each of these costs, including underlying assumptions, model framework and methodology, and data analysis, is discussed in detail.**

| | |
|---|---|
| 17. Key Words<br>**Bus, buses, CMV, commercial motor vehicle, cost, costs, crashes, environment, environmental, fuel** | 18. Distribution Statement<br>**No restrictions** |

| | | | |
|---|---|---|---|
| 19. Security Classif. (of this report)<br>**Unclassified** | 20. Security Classif. (of this page)<br>**Unclassified** | 21. No. of Pages<br>**132** | 22. Price |

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

# SI* (MODERN METRIC) CONVERSION FACTORS

## TABLE OF APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| in$^2$ | square inches | 645.2 | square millimeters | mm$^2$ |
| ft$^2$ | square feet | 0.093 | square meters | m$^2$ |
| yd$^2$ | square yards | 0.836 | square meters | m$^2$ |
| ac | acres | 0.405 | hectares | ha |
| mi$^2$ | square miles | 2.59 | square kilometers | km$^2$ |
| | | **VOLUME** | 1,000 L shall be shown in m$^3$ | |
| fl oz | fluid ounces | 29.57 | milliliters | ml |
| gal | gallons | 3.785 | liters | L |
| ft$^3$ | cubic feet | 0.028 | cubic meters | m$^3$ |
| yd$^3$ | cubic yards | 0.765 | cubic meters | m$^3$ |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2,000 lb) | 0.907 | megagrams (or “metric ton”) | mg (or “t”) |
| | | **TEMPERATURE** | | |
| °F | Fahrenheit | 5 × (F-32) ÷ 9<br>or (F-32) ÷ 1.8 | Temperature is in exact degrees Celsius | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-lamberts | 3.426 | candela/m$^2$ | cd/m$^2$ |
| | | **Force and Pressure or Stress** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/in$^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

## TABLE OF APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| mm$^2$ | square millimeters | 0.0016 | square inches | in$^2$ |
| m$^2$ | square meters | 10.764 | square feet | ft$^2$ |
| m$^2$ | square meters | 1.195 | square yards | yd$^2$ |
| ha | hectares | 2.47 | acres | ac |
| km$^2$ | square kilometers | 0.386 | square miles | mi$^2$ |
| | | **VOLUME** | | |
| ml | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| m$^3$ | cubic meters | 35.314 | cubic feet | ft$^3$ |
| m$^3$ | cubic meters | 1.307 | cubic yards | yd$^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| mg (or “t”) | megagrams (or “metric ton”) | 1.103 | short tons (2,000 lb) | T |
| | | **TEMPERATURE** | | |
| °C | Celsius | 1.8C + 32 | Temperature is in exact degrees Fahrenheit | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/m$^2$ | candela/m$^2$ | 0.2919 | foot-lamberts | fl |
| | | **Force & Pressure Or Stress** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/in$^2$ |

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003, Section 508-accessible version September 2009.)

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# ABBREVIATIONS AND ACRONYMS

| Acronym | Definition |
|---|---|
| AADT | average annual daily traffic |
| ATR | automatic traffic recorder |
| CMV | commercial motor vehicle |
| EPA | Environmental Protection Agency |
| FARS | Fatality Analysis Reporting System |
| FHWA | Federal Highway Administration |
| GES | General Estimates System |
| HERS | Highway Economic Requirements System |
| HM | hazardous materials |
| HMIS | Hazardous Materials Incident System |
| HPMS | Highway Performance Monitoring System |
| ISO | Insurance Services Office |
| KABCO | A scale of crash severity ranging from fatality to property damage only |
| MCMIS | Motor Carrier Management Information System |
| MOVES | Motor Vehicle Emissions Simulator (primary EPA model for estimating traffic emissions) |
| PDO | property-damage-only |
| PHMSA | Pipeline and Hazardous Materials Safety Administration |
| QALY | quality-adjusted life year |
| TSIS-CORSIM | Traffic Software Integrated System - Corridor Simulation |
| TSD | time step data |
| vph | vehicles per hour |

| **Acronym** | **Definition** |
|---|---|
| VMS | variable message signs |
| VMT | vehicle miles traveled |
| VOC | volatile organic compounds |
| VSL | value of a statistical life |
| VOT | value or opportunity cost of travel time |
| VSP | vehicle specific power |

# EXECUTIVE SUMMARY

This report presents estimates of certain categories of costs of commercial motor vehicle (CMV) crashes. These estimates will provide the Federal Motor Carrier Safety Administration (FMCSA) with a more comprehensive view of the total costs of truck and bus crashes from which to inform policy decisions related to CMV safety.

## SCOPE OF COSTS

The primary components of crash costs are shown in Figure 1. Crash costs estimated as part of this study are the shaded cells, and include property damage, vehicle delay costs, emissions costs, and excess fuel consumption costs. The item “Lost Productivity” estimated in previous studies includes both lost work time from injuries and additional travel time resulting from crash-caused traffic queues (i.e., backups), but the present study only addresses the latter. Quality-Adjusted Life Year (QALY) is a dollar amount assigned to the value of life for analytical purposes. Volatile organic compounds (VOC) are pollutants formed during complete and incomplete combustion of fuel. Additional emissions and additional fuel consumption from crash queues are also estimated, as well as spilled fuel and emissions from ruptured motor fuel tanks.

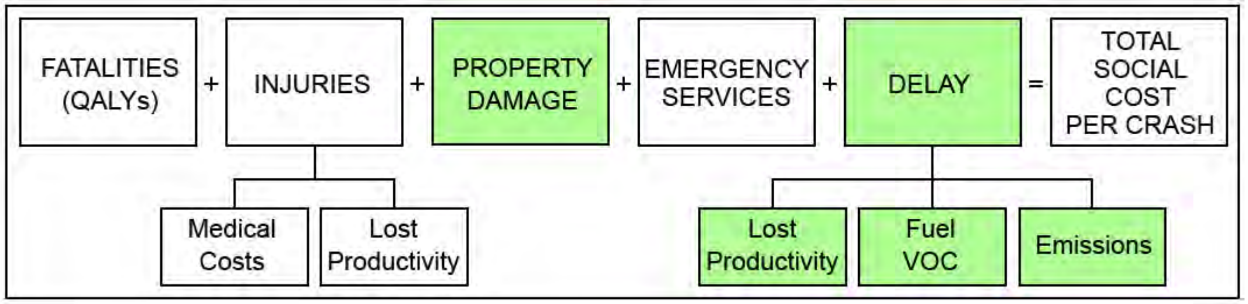


**Figure 1. Flow Chart. Crash Cost Components**

In addition, this report also develops improved methods for estimating costs specific to crashes involving hazardous material (HM) releases. The development of each of these costs, including underlying assumptions, model framework, methodology, and data analysis, is discussed in detail in the body of the report.

Combining the results from this study with previous estimates of other categories of costs (value of lives lost and injuries, lost productivity from injured victims, medical costs, and emergency response costs) will produce a full accounting of all costs associated with a CMV crash. The primary motivation for this work is to provide FMCSA with the information relating to the costs of CMV crashes for inclusion in benefit cost analysis of future regulatory and program evaluations.

## PROPERTY DAMAGE COSTS

Updated estimates of property damage caused by CMV-involved crashes are based on recent Insurance Services Office (ISO) data that describe insurance claims from CMVs. The method used to estimate costs from these data corrects for potentially serious data truncation issues inherent in the insurance data. The problem of data truncation arises because a (potentially) large number of small crashes may not result in a motor carrier filing a collision insurance claim, especially if the cost of the damage is less than the policy deductible. The nature of the data truncation is depicted in Figure 2.

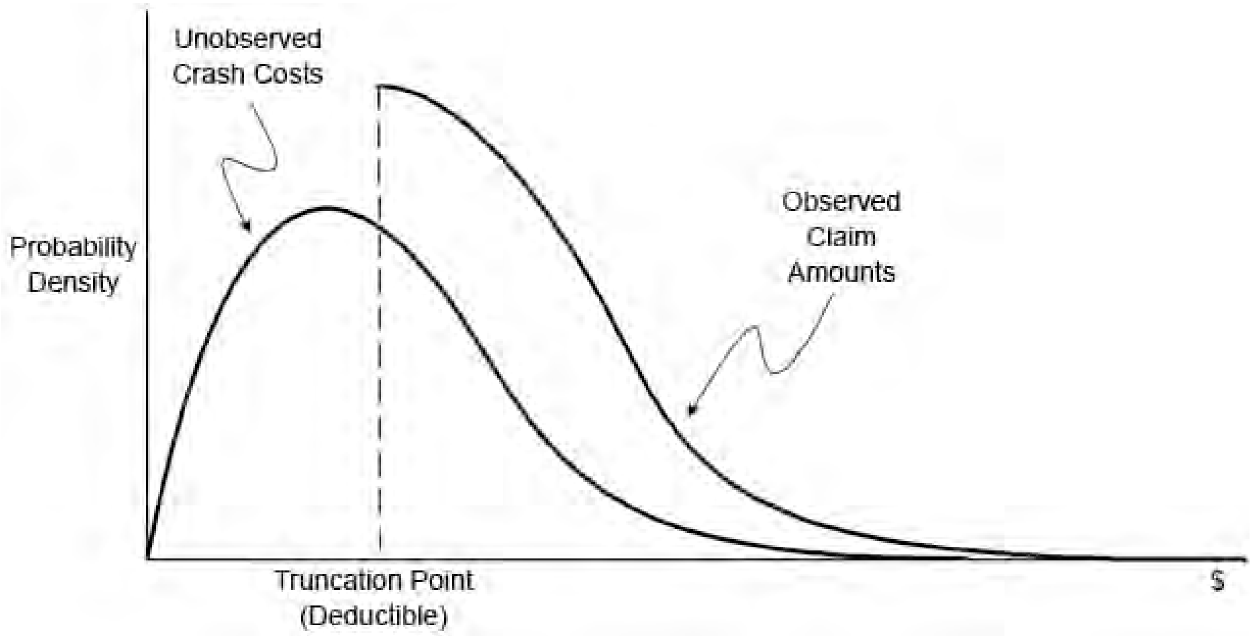


**Figure 2. Truncated Distribution Versus Complete Distribution**

The estimated average property damage costs for various truck size categories are presented in Table 1.

**Table 1. Estimated Property Damage per Crash by Truck Type**

| Truck Type | Mean Damage Cost[1] |
|---|---:|
| Medium Trucks | $9,740 |
| Heavy Trucks | $14,102 |
| Heavy Trucks—Tractors | $17,558 |
| Extra Heavy Trucks | $25,253 |
| Extra Heavy Trucks—Tractors | $21,795 |
| Overall Average | $15,252 |

---

[1] Calculated from ISO data

## DELAY AND RELATED COSTS

### Framing the Analysis

This report estimates the costs of delay (in time, additional fuel burn, and emissions created) for users on the roadway where a crash has occurred, users of roadways to which users are diverted from the crash site, and non-users affected by crash-induced air pollution. CMV crashes force some vehicles to idle in a traffic backup and also compel some drivers to use an alternate longer route around the accident site. Both activities increase aggregate travel time, fuel consumption, and emissions.

For the models developed here, the primary drivers of the above costs are as follows:

- The characteristics of the roadway.
- The volume of traffic on the roadway.
- The duration of the road closure due to the crash.

Roadways are categorized into five representative roadway types, with the traffic volume on the roadway varied within each type to represent different times of day and days of the week when a crash could occur, and the duration of road closure determined empirically. Estimates of delay costs are developed for various combinations of those attributes and the resulting cost estimates are weighted by the frequency with which each type of crash occurs to develop estimates of expected crash costs for various subcategories. Costs can be tabulated separately by the severity of a crash (e.g., fatal, injury only, or property damage only [PDO]) or aggregated into a single global average. For tabulations by severity, crash duration is assumed to be affected by severity.

Delay estimates are used as an input to models that estimate costs of emissions and fuel consumption due to traffic disruptions on a roadway where a crash has occurred.

### Roadway Types

Five prototypical roadway types are modeled. The capacities and vehicle mix for those roadway types are derived from Highway Performance Monitoring System (HPMS) data. Different scenarios for each roadway type involve various traffic volumes and durations of road closures. The scenarios and some of the parameters are shown in Table 2. Average speed limit, average annual daily traffic (AADT), and the vehicle mix for each roadway type is the median weighted value of vehicle miles traveled (VMT) for the specified functional classes with the specified number of lanes.

**Table 2. Characteristics of Roadway Types for Modeling**

| Roadway Type | Number of Lanes (Both Directions) | Average Speed | AADT | Traffic Volume Comprised of Passenger Cars | Traffic Volume Comprised of Single-Unit Trucks | Traffic Volume Comprised of Combination Trucks |
|---|---|---|---|---|---|---|
| Urban Interstate/Expressway | 6 | 60 mi/h | 107,410 | 92% | 3% | 5% |
| Urban Arterial | 4 | 45 mi/h | 27,731 | 95% | 3% | 2% |
| Urban Other | 2 | 35 mi/h | 9,474 | 96% | 3% | 1% |
| Rural Interstate/Principal Arterial | 4 | 65 mi/h | 25,528 | 80% | 4% | 16% |
| Rural Other | 2 | 55 mi/h | 4,297 | 91% | 5% | 4% |

Traffic volumes for the simulations are drawn from daily traffic volume distributions developed for each roadway type under consideration. The distributions are based on extensive sample traffic counts collected by States and submitted to the Federal Highway Administration (FHWA). Using modeled typical traffic volume at the time of a crash increases the precision of the delay estimates. Rather than using daily averages, the distributions provide more accurate volumes that can be applied to crashes by hour, at different times of day and day of the week. Daily distributions also describe the evolution of traffic flow over the course of a longer duration crash. An example of one of these constructed distributions is shown in Figure 3.

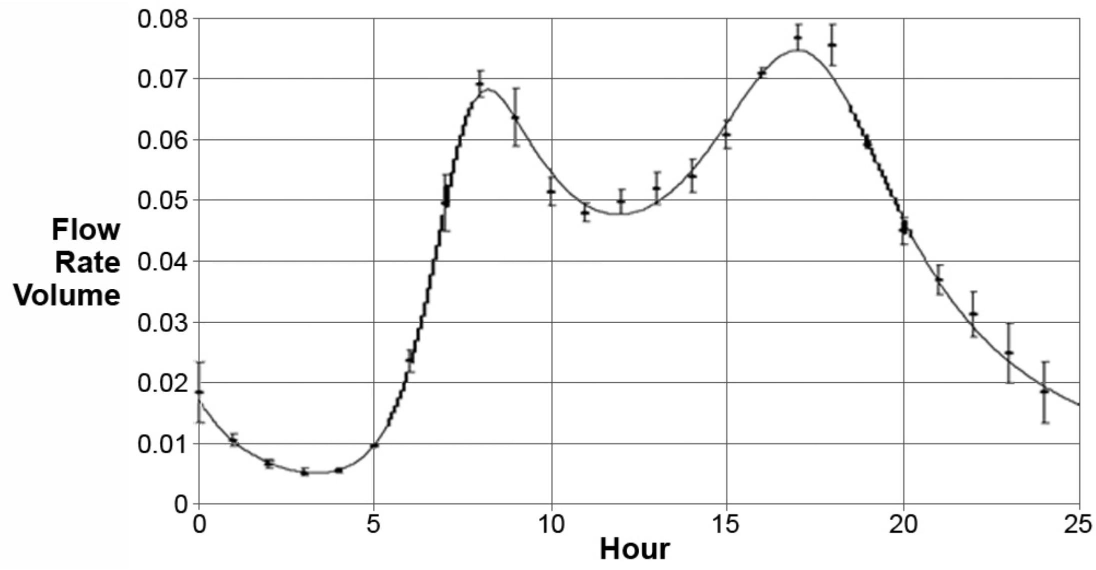


**Figure 3. Fitted Distribution of Traffic Volume Hourly Averages for Weekday Urban Expressways**

Distributions of roadway closure duration were based on incident duration data obtained from the State departments of transportation of Pennsylvania and Kentucky.

### Incident Delay Microsimulations

Estimates of direct crash delay are obtained from the Traffic Software Integrated System Corridor Simulation (TSIS-CORSIM) traffic microsimulation model. TSIS-CORSIM allows the analyst to simulate different traffic patterns under different situations by varying the characteristics of the roadway, traffic volume, traffic speed, driver aggressiveness, and other parameters. Crashes are simulated by introducing blockages on the roadway that close certain lanes for predefined sets of time to represent the time needed to clear a crash site. The simulation traces the effects of traffic as a backup builds following a crash that has completely or partially blocked a roadway that reduces roadway capacity below the volume of traffic on it. An example snapshot of a simulated crash is shown in Figure 4.

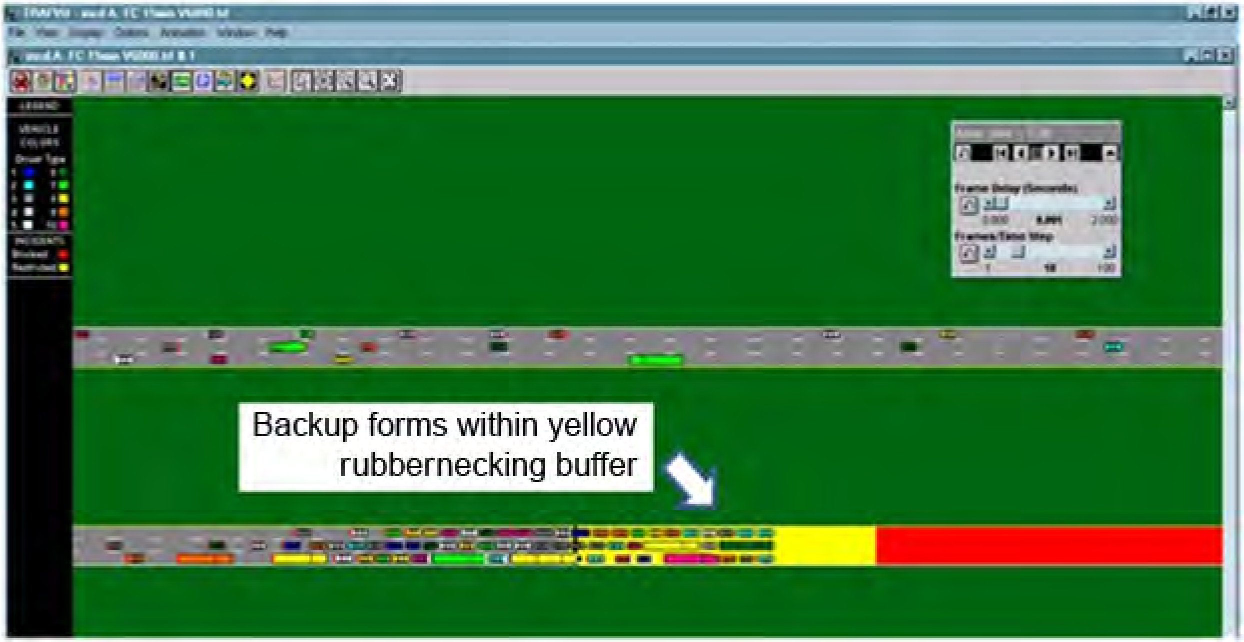


Figure 4. Incident Simulation on an Urban Interstate/Expressway

In some instances where road volumes are low, a partial closure may have limited impact because enough capacity remains to serve the low traffic volumes. The simulation continues after the blockage is removed to capture dissipation of the backup as traffic flow returns to normal. The simulation is run both with an incident and for conditions without an incident to measure the incremental delay from the crash. All results presented here are “net” figures where the baseline estimates of delay, emissions, and fuel consumption have been deducted from the estimates of those items for each crash scenario simulation. Also, each scenario is run multiple times to allow for random variation in driver behaviors. The delay estimates reported here use the median value from those multiple runs.

### Network Delay

Crash simulations provide an estimate of the amount of delay experienced by drivers traveling the road segment on which a given crash occurs. Some severe crashes with a long duration may also cause delay for drivers using alternate and parallel routes.

This dynamic is not captured in the microsimulation delay estimates. Such alternate route delay would stem from main route drivers voluntarily diverting, or being diverted around the crash site, thereby interacting with alternate route drivers. To calculate delay stemming from crashes above a certain level of severity (as determined by duration, volume, and degree of lane closure), a secondary diversion delay model was developed. The diversion delay model is based on deterministic queuing (traffic backup) theory and its delay estimates are combined with estimates from the primary traffic delay simulation model to provide total delay for each volume-facility-duration scenario. An example delay graph from the diversion model is shown in Figure 5.

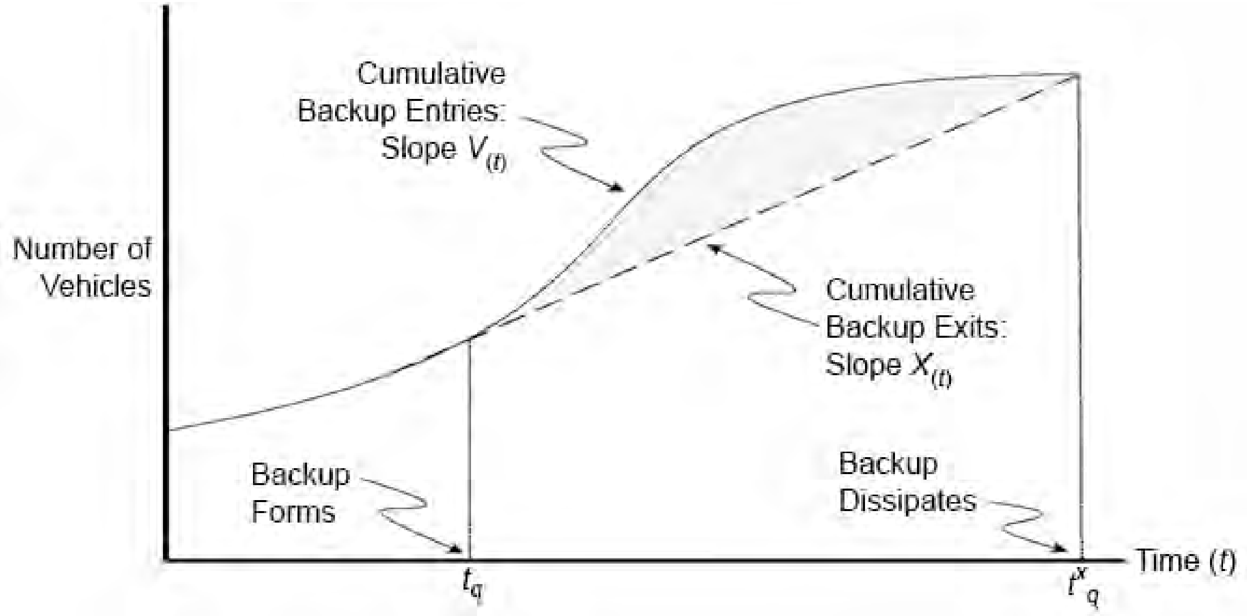


**Figure 5. Deterministic Queuing Model for Diversion Delay**

Microsimulations are performed for just a subset of the possible combinations of roadway type, closure duration, and volumes. These simulated data points along with data from the network delay model were used to estimate an all-encompassing model of delay. Thus delay estimates for a wider set of conditions are interpolated and extrapolated from the data from the microsimulations and diversion models.

### Aggregation of Individual Crashes into Average Costs per Crash

The estimates of delay and emissions generated by the simulation modeling are used to develop estimates of costs attributable to individual crashes of various types. Data describing the frequency of those various types of CMV crashes is needed to transform those individual estimates into generalized expected values of the costs of CMV crashes. Using national vehicle crash records from the General Estimates System (GES) (for non-fatal crashes) and the Fatality Analysis Reporting System (FARS) (for fatal crashes) a representative distribution of crashes across roadway type and severity is determined. Hours of vehicle delay are monetized using a value of time estimate discussed in the body of the report.

## Emissions and Excess Fuel Consumption From Delay

Emissions are modeled using a unique and novel approach. The data created by TSIS-CORSIM to drive an animation software tool is re-purposed to provide data to the Environmental Protection Agency (EPA) Motor Vehicle Emission Simulator (MOVES) model, which performs vehicle emissions modeling. The animation data file can be used to generate descriptions of vehicle starts, stops, acceleration, and deceleration. Incorporating this vehicle drive cycle information provides more accurate estimates of emissions and fuel consumption than the TSIS-CORSIM or MOVES models. This method appears to be the first to combine the two models in this way.

A series of emissions estimates are produced for each simulated crash scenario. To fill in the missing data points (i.e., for crash durations not modeled) the emissions data were linearly interpolated between missing values and extrapolated to higher levels of crash duration not explicitly modeled, based on vehicle hours of delay.

Additional emissions are valued at their social costs as presented in various policy research documents. Finally, fuel consumption is valued at the retail prices of gasoline and diesel, including fuel excise taxes. Table 3, Table 4, and Table 5 present the estimates of costs of delay, emissions, and fuel consumption respectively, by roadway type and crash severity.

Delay costs per crash vary widely among roadway types because urban expressways have much greater volumes than rural local roads. Because fatal crashes have longer closure durations, they also tend to be more expensive. If a regulatory action has differential impacts on roadway types or severity levels, the estimated benefits of the action can be matched to the associated costs per crash.

**Table 3. Estimated Delay Time Cost per Crash (2010 Dollars)**

| Roadway Type | Fatal | Injury Only | PDO | Average for Road Type |
|---|---:|---:|---:|---:|
| Urban Interstate/Expressway | $163,792 | $61,395 | $52,175 | $55,121 |
| Urban Arterial | $11,760 | $3,328 | $2,649 | $2,876 |
| Urban Other | $11,303 | $3,860 | $3,258 | $3,458 |
| Rural Interstate/Principal Arterials | $7,086 | $2,628 | $2,222 | $2,351 |
| Rural Other | $2,421 | $821 | $684 | $729 |
| **Average for All Roadway Types** | **$39,602** | **$14,508** | **$12,280** | **$12,996** |

Table 4. Estimated Cost of Emissions per Crash (2010 Dollars)

| Roadway Type | Fatal | Injury Only | PDO | Average for Road Type |
|---|---|---|---|---|
| Urban Interstate/Expressway | $3,019 | $1,132 | $962 | $1,016 |
| Urban Arterial | $584 | $165 | $132 | $143 |
| Urban Other | $172 | $64 | $54 | $57 |
| Rural Interstate/Principal Arterial | $718 | $245 | $207 | $220 |
| Rural Other | $238 | $81 | $67 | $72 |
| **Average for All Roadway Types** | **$951** | **$338** | **$285** | **$302** |

Table 5. Estimates of Cost of Excess Fuel Burn per Crash (2010 Dollars)

| Roadway Type | Fatal | Injury Only | PDO | Average Road Type |
|---|---|---|---|---|
| Urban Interstate/Expressway | $6,544 | $2,453 | $2,084 | $2,202 |
| Urban Arterial | $1,801 | $510 | $406 | $440 |
| Urban Other | $545 | $202 | $171 | $181 |
| Rural Interstate/Principal Arterial | $1,194 | $408 | $344 | $365 |
| Rural Other | $499 | $169 | $141 | $150 |
| **Average for All Roadway Types** | **$2,147** | **$757** | **$636** | **$675** |

## HAZARDOUS MATERIAL-SPECIFIC COSTS

A small share of CMV crashes involves some type of HM, such as gasoline, nitrogen fertilizer, or fireworks. The bulk of this report uses data sources that cover all CMV crashes, which includes the crashes involving HM. Hence, the estimates of average costs of CMV crashes using these data sources include the costs of HM crashes in proportion to the prevalence of HM crashes in the universe of all CMV crashes.

For some purposes, however, it may be desirable to have crash costs specifically for HM crashes. The primary data source for estimating HM crash costs is the Pipeline and Hazardous Materials Safety Administration's (PHMSA) Hazardous Materials Information System (HMIS), which provided cost and material type for a large number of HM crashes. Although this dataset was rich with crash-specific detail, it lacked information on truck configurations. The Motor Carrier Management Information System (MCMIS) does, however, contain such data. There are sufficient overlapping characteristics in both datasets to allow a portion of the HM crash records to be matched between them, which provide a more complete description of HM crashes.

Using data from the HMIS database, the average cost of damages (the total across all recorded cost categories) was $129,141 with a median of $63,885. The point estimates and 95-percentile interval for the mean are presented in Table 6. The histogram presented in Figure 6 shows the distribution of HM-related damages.

**Table 6. Distribution of Damages from HM Crashes (2010 Dollars)**

| N | Mean | 5th Percentile | 25th Percentile | 50th Percentile | 75th Percentile | 95th Percentile |
|---|---|---|---|---|---|---|
| 3,363 | $129,141 | $ 0 | $12,169 | $63,885 | $139,446 | $402,458 |

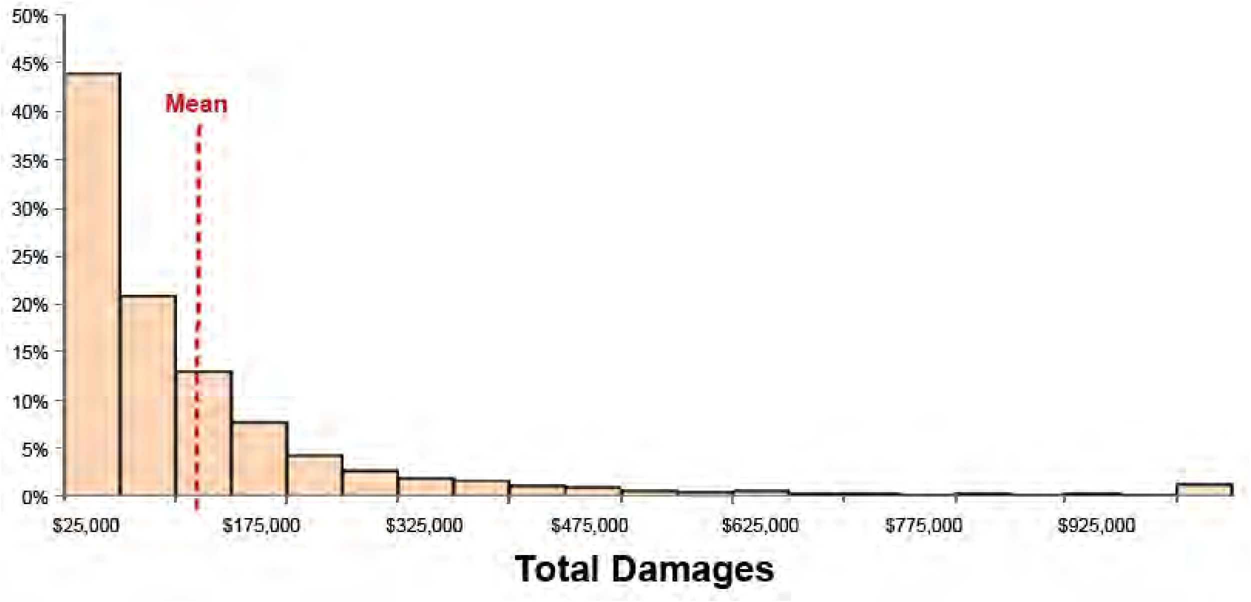


Figure 6. Histogram of Total Damages

Estimates of the costs of delay, emissions, and fuel burn that are specific to HM crashes can be found in Section 4.

[This Page Intentionally Left Blank]

# 1. FRAMEWORK FOR CRASH COST ESTIMATION

This report presents the results of a study to develop analytical models for estimating selected categories of costs of commercial motor vehicle (CMV)-involved crashes.[2] Specifically, the estimated costs are associated with property damage, delay, emissions, and the additional consumption of fuel due to a CMV crash. These costs represent only a portion of the monetary or economic consequences of CMV crashes, which also include lost lives, emergency service response, and injuries. Nevertheless, the results from this study can be combined with cost estimates for the other components of CMV crashes that have been developed in other studies, as shown in Figure 7. In this way, a full accounting of total CMV crash costs can be estimated.[3]

Quality-Adjusted Life Year (QALY) is a dollar amount assigned to the value of life for analytical purposes. Volatile organic compounds (VOC) are pollutants formed during complete and incomplete combustion of fuel. Additional emissions and additional fuel consumption from crash queues are also estimated, as well as spilled fuel and emissions from ruptured motor fuel tanks.

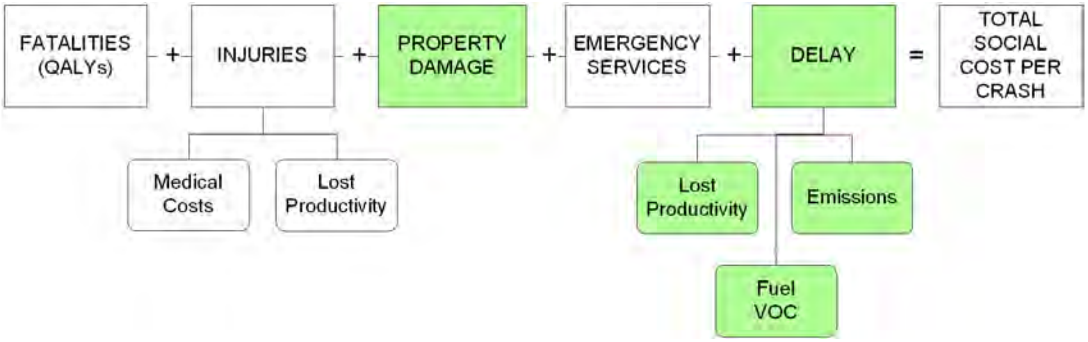


**Figure 7. Flow Chart. Crash Cost Components**

A highly flexible and adaptive strategy was followed for estimating the particular CMV crash costs within the scope of this study. Incident delay, especially, required an eclectic and demanding set of steps to transform available empirical data into useful estimates of delay caused by crashes. This section provides an overview of these strategies.

There are no numbers for total average crash costs presented in this report. Some of the costs that would need to be included are not within the scope of the present study, and the relevant numbers from other studies would need to be updated for compatibility. Also, some of the present results (for hazardous material [HM] crashes) are already included in the data.

## 1.1 PRIOR WORK IN VEHICLE CRASH COSTING

A series of reports concerning the full costs of highway crashes has been published over the past 20 or so years. Initially directed to all motor vehicles using U.S. highways, attention has focused

---

[2] Commercial vehicle crashes include truck crashes and motor coach crashes, but not school and transit buses.

[3] For example, CMV crash costs presented in this report can be combined with estimates of the medical, emergency services or lost productivity costs of CMV crashes generated in previous work in this area by Zaloshnja and Miller (2007).

more recently on truck crashes. The authors for this work include Eduard Zaloshnya and Ted Miller.

### 1.1.1 Zaloshnja and Miller

Crash costs have been used in the evaluation of highway traffic regulation for several decades. Estimates, particularly for truck-involved crashes, were developed by the Federal Highway Administration (FHWA) in the early 1990s, when trucking safety was within its scope of responsibility, and subsequently extended by the Federal Motor Carrier Safety Administration (FMCSA). The current estimates of the costs of truck crashes are from the work of Zaloshnja and Miller.[4] They estimate costs of truck crashes in the following cost categories:

- Medical costs.
- Emergency services.
- Property damage.
- Lost productivity from delays.
- Total lost productivity.[5]
- Monetized quality-adjusted life years (QALYs) based on the value of a statistical life (VSL).

These are included in the scope of costs shown in Figure 1, but emissions are omitted from the above list. Productivity consists of person-hours of lost time, working time in the case of injuries and delay time in the case of incident delay. Table 7 presents costs per crash for the six truck categories in Zaloshnja and Miller (2007), and also aggregated for each of seven injury severity categories. Not surprisingly, the vast bulk of crashes result in no personal injury and are relatively inexpensive, while the small share of crashes that result in at least 1 fatality are 10 times more costly per crash.

### 1.1.2 Aggregation by Crash Severity

Preserving the detail of truck type and severity creates a very fine granularity, or detail, and is difficult to support with existing or likely data. This level of granularity is also unlikely to be needed for policy analysis, but maintaining it to the extent feasible provides a capability for maximizing the match between policy and data.

The bottom of Table 8 collapses the truck types into one class, showing costs per crash by severity only. Incident delay varies by severity in mostly expected ways, although the delay cost for the C-level (possible injury) is greater than for either the B-level (non-incapacitating injury) or the A-level (incapacitating injury) for unknown reasons.

### 1.1.3 Aggregation by Truck Type

Aggregating over severity levels results in the average crash costs shown in Table 8. Crashes involving combination rigs with two or more trailers are dramatically more costly per crash than

---

[4] See Zaloshnja, Miller, and Spicer (2000), Zaloshnja and Miller (2004), Zaloshnja and Miller (2007).

[5] Total Lost Productivity is the sum of Lost Productivity from Delays and Lost Productivity to people injured in the crash.

other truck configurations, but the multi-trailer group is the smallest of the “known” categories. Single-trailer combinations (semis or 18-wheelers) are considerably more expensive than the next-largest category, straight (single unit) trucks. If an FMCSA or other program or regulation has differential effects between single versus combination trucks, or between single semis versus multiple combinations, the cost savings per crash avoided can be tied to the applicable mix of truck types.

**Table 7. Costs per Medium/Heavy Truck Crash by Truck Type Involved in Crash and Police-Reported Maximum Injury Severity, 2001–03 (in 2005 Dollars)**

| Truck Type Involved in Crash | Maximum Injury Severity in Crash | Annual Number of Crashes | Average Number of People Involved in Crash | Medical Costs | Emer-gency Services | Property Damage | Lost Pro-ductivity From Delays | Total Lost Produc-tivity | Monetized QALYs Based on VSL $3 Million | Total Cost per Crash | QALY |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Straight Truck, No Trailer | 0—No injury | 116,476 | 1.24 | 253 | 132 | 4,730 | 5,417 | 7,431 | 740 | 13,286 | 0.0062 |
| | C—Possible injury | 17,491 | 1.59 | 8,396 | 399 | 8,404 | 10,656 | 24,673 | 20,493 | 62,364 | 0.1715 |
| | B—Non-incapacitating injury | 4,665 | 1.51 | 15,903 | 203 | 7,482 | 8,337 | 86,964 | 87,673 | 198,225 | 0.7337 |
| | A—Incapacitating injury | 2,612 | 1.59 | 84,052 | 603 | 11,139 | 10,411 | 223,154 | 321,546 | 640,494 | 2.691 |
| | K—Killed | 1,016 | 1.61 | 48,893 | 1,149 | 19,676 | 11,409 | 962,119 | 2,104,573 | 3,136,409 | 17.6134 |
| | U—Injury, severity unknown | 527 | 1.4 | 5,398 | 377 | 8,232 | 9,083 | 18,804 | 11,496 | 44,307 | 0.0962 |
| | Unknown | 7,245 | 1.34 | 1,286 | 234 | 5,632 | 7,735 | 11,786 | 3,176 | 22,114 | 0.0266 |
| Straight Truck with Trailer | 0—No injury | 12,502 | 1.21 | 1,272 | 140 | 6,740 | 5,763 | 7,870 | 1,273 | 17,295 | 0.0107 |
| | C—Possible injury | 1,359 | 1.59 | 13,681 | 475 | 14,852 | 11,384 | 28,075 | 34,447 | 91,530 | 0.2883 |
| | B—Non-incapacitating injury | 517 | 1.49 | 14,110 | 279 | 17,084 | 12,706 | 96,369 | 92,597 | 220,440 | 0.775 |
| | A—Incapacitating injury | 594 | 2.1 | 34,573 | 507 | 16,138 | 10,772 | 181,926 | 130,292 | 363,436 | 1.0904 |
| | K—Killed | 162 | 1.73 | 58,694 | 1.089 | 25,788 | 10,028 | 932,569 | 2,124,691 | 3,142,831 | 17.7817 |
| | U—Injury, severity unknown | 20 | 2.25 | 2,230 | 375 | 18,028 | 11,502 | 19,347 | 6,011 | 45,990 | 0.0503 |
| | Unknown | 1,277 | 1.15 | 2, 053 | 186 | 7,623 | 5,664 | 9,419 | 4,116 | 23,396 | 0.0344 |
| Bobtail | 0—No injury | 9,843 | 1.25 | 984 | 132 | 6,332 | 6,892 | 9,598 | 2,042 | 19,089 | 0.0171 |

| Truck Type Involved in Crash | Maximum Injury Severity in Crash | Annual Number of Crashes | Average Number of People Involved in Crash | Medical Costs | Emer-gency Services | Property Damage | Lost Pro-ductivity From Delays | Total Lost Produc-tivity | Monetized QALYs Based on VSL $3 Million | Total Cost per Crash | QALY |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | C—Possible injury | 1,269 | 1.59 | 8, 015 | 363 | 11,459 | 13,246 | 27,778 | 16,709 | 64,324 | 0.1398 |
| | B—Non-incapacitating injury | 266 | 1.6 | 10,835 | 197 | 9,936 | 9,273 | 96,472 | 56,066 | 173,507 | 0.4692 |
| | A—Incapacitating injury | 858 | 1.58 | 36,300 | 500 | 9,985 | 8,127 | 117,368 | 217,195 | 381,348 | 1.8177 |
| | K—Killed | 37 | 1.45 | 39, 249 | 1.126 | 26,663 | 12,430 | 971,748 | 2,133,782 | 3,172,568 | 17.8578 |
| | U—Injury, severity unknown | 59 | 1.04 | 1, 414 | 278 | 8,828 | 6,269 | 9,398 | 3,005 | 22,923 | 0.0251 |
| | Unknown | 786 | 1.14 | 1,586 | 158 | 7,484 | 5,915 | 9,402 | 3,770 | 22,401 | 0.0316 |
| Truck-Tractor, 1 Trailer | 0—No injury | 179,181 | 1.12 | 1, 119 | 120 | 6,493 | 5,024 | 6,867 | 1,151 | 15,749 | 0.0096 |
| | C—Possible injury | 19,461 | 1.53 | 13,010 | 460 | 15,410 | 10,506 | 26,590 | 35,489 | 90,959 | 0.297 |
| | B—Non-Incapacitating injury | 17,688 | 1.49 | 15,828 | 205 | 12,832 | 7,909 | 75,649 | 67,197 | 171,710 | 0.5624 |
| | A—Incapacitating injury | 10,843 | 1.57 | 53,003 | 510 | 16,329 | 9,528 | 152,532 | 215,471 | 437,845 | 1.8033 |
| | K—Killed | 2,825 | 1.58 | 81,335 | 1,495 | 39,366 | 14,941 | 1, 200,333 | 2,511,192 | 3,833,721 | 21.0164 |
| | U—Injury, severity unknown | 413 | 1.19 | 5,425 | 195 | 10,329 | 7,042 | 12,998 | 4,450 | 33,397 | 0.0372 |
| | Unknown | 10,191 | 1.49 | 2,131 | 196 | 8,997 | 6,079 | 9,685 | 3,929 | 24,939 | 0.0329 |
| Truck-Tractor, 2 or 3 | 0—No injury | 4,976 | 1.03 | 1,059 | 111 | 16,350 | 4,568 | 6,280 | 1,084 | 24,883 | 0.0091 |
| | C—Possible injury | 740 | 1.49 | 12,207 | 465 | 44,308 | 10,971 | 26,400 | 33,541 | 116,920 | 0.2807 |

| Truck Type Involved in Crash | Maximum Injury Severity in Crash | Annual Number of Crashes | Average Number of People Involved in Crash | Medical Costs | Emer-gency Services | Property Damage | Lost Pro-ductivity From Delays | Total Lost Produc-tivity | Monetized QALYs Based on VSL $3 Million | Total Cost per Crash | QALY |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Trailers | B—Non incapacitating injury | 559 | 1.32 | 11,766 | 252 | 48,302 | 10,609 | 90,780 | 92,984 | 244,084 | 0.7782 |
| | A—Incapacitating injury | 1,129 | 1.26 | 140,004 | 828 | 58,279 | 11,729 | 458,351 | 634,474 | 1,291,936 | 5.31 |
| | K—Killed | 150 | 1.5 | 61,309 | 1,295 | 98,318 | 12,726 | 1,001,712 | 2,190,118 | 3,352,753 | 18.3293 |
| | U—Injury, severity unknown | – | – | – | – | – | – | – | – | – | – |
| | Unknown | 420 | 1.09 | 1,681 | 191 | 17,889 | 5,214 | 8,114 | 2,998 | 30,872 | 0.0251 |

Annual number of fatal crashes estimated from 2001–03 FARS, annual number of crashes with maximum severity not A, B, or K estimated from 2001–03 GES 2001–03, and the rest from the 2001–03 Large Truck Crash Causation Study (LTCCS)

Source: Zaloshnja and Miller (2007).

**Table 8. Summary of Zaloshnja and Miller (2007) Costs per Crash by Truck Type Involved in Crash, 2001–03 (in 2005 Dollars)**

| Truck Crash Type | Annual Number of Crashes | Medical Costs | Emergency Services | Property Damage | Lost Productivity From Delays | Total Lost Productivity | Monetized QALYs Based on VSL=$3 Million | Total Cost Per Crash |
|---|---|---|---|---|---|---|---|---|
| Straight Truck, No Trailer | 150,032 | 3,545 | 186 | 5,512 | 6,371 | 22,385 | 25,735 | 56,296 |
| Straight Truck with Trailer | 16,430 | 4,535 | 198 | 8,346 | 6,668 | 27,862 | 32,691 | 71,758 |
| Bobtail | 13,118 | 4,320 | 185 | 7,279 | 7,590 | 22,900 | 24,816 | 58,055 |
| Truck Tractor, 1 Trailer | 240,601 | 6,492 | 191 | 8,622 | 6,047 | 34,228 | 48,041 | 97,574 |
| Truck Tractor, 2 or 3 Trailers | 7,974 | 23,680 | 281 | 28,746 | 6,788 | 96,917 | 141,549 | 289,549 |
| Unknown Medium/Heavy Truck | 5,717 | 3,219 | 176 | 7,196 | 5,164 | 25,171 | 39,868 | 63,343 |
| All Medium/Heavy Trucks | 433,872 | 5,606 | 191 | 7,847 | 6,231 | 30,582 | 40,655 | 91,112 |

Incident delay, however, is not particularly related to truck type. Severity is likely to be higher for the heavier combinations, resulting in longer closure duration. Semis are more prevalent on rural interstates than on local roads, suggesting shorter durations for single-unit trucks. These relationships are in the nature of weak statistical regularities, so that although the column "Lost Productivity From Delays" shows some variation among truck types, it is difficult to know how much of this is functional and how much is an artifact of the methodology. Because emissions are closely tied to delay, as well as to the vehicle mix in the backup, emissions estimates can be expected to show the same patterns. The methodology for estimating delay (lost productivity) in Table 7 and Table 8 is not documented, but is assumed to be unconnected to the actual volume of traffic on the road where the crash occurred because this information is not available in police reports.

These tables illustrate the kinds of variables and tabulations that have been calculated previously. The present study generates more accurate estimates of delay costs, adds estimates for environmental emissions and increased fuel consumption, and permits these and other costs to be tabulated by roadway type (provides revised property damage estimates). Tabulations by roadway type will not show variations by truck type in injury costs, for example, and tabulations by truck type will not show variations in incident delay by roadway type. Time of day and day of the week can be incorporated, although the software for performing the calculations is not currently very user-friendly.

## 1.2 CRASH-COST MODEL REQUIREMENTS

CMV-involved crash costs must be assembled using data from several sources and a methodology adapted to the data and the nature of the costs. For some of the cost categories covered in the report, it is important to preserve details of the distributions of variables, not simply their average values, even though the desired end result is a single average or expected value. The three reasons for maintaining this distributional detail or disaggregation are as follows:

- FMCSA policies may affect segments of the CMV freight/passenger industry differently, and for policy analysis purposes the evaluation of the policy should reflect the specifics of the expected impacts (e.g., combination trucks, long-haul service).
- For non-linear distributions, the average of the distribution is not obtained by using average values of the input parameters.
- The average result of the interaction of two nonlinear distributions is not calculated from the average values of each variable, but requires the full distribution of both variables (e.g., total delay as a function of traffic volume and duration of the closure).

### 1.2.1 Characteristics of Policy Options

FMCSA programs and policies are intended to reduce the frequency and costs of CMV crashes. Any given regulation—hours of service, driver registry, speed limiters (engine governors), mandatory insurance liability—will affect the likelihood of some crashes more than others. Ideally, the estimation of the benefits of the program should reflect the costs of the particular crashes avoided.

Anticipating the needs of future regulatory evaluations is, of course, speculative, but providing a variety of ways in which the cost-per-crash calculations can be tabulated will provide at least some improvement in accuracy. The major dimensions incorporated in this study are roadway type, such as two lane roads versus expressways, and location—either urban or rural.

### 1.2.2 Averages of Single Distributions

Sometimes the variability of the measure is as important as its average. For example, total delay from the temporary closure of a transportation link—e.g., a grade crossing—depends upon the duration of the closure, the volume of arrivals during the closure, and the capacity of the roadway to dissipate the backup. Ten closings of the same duration and same arrival volume will result in delay that is 10 times the single closing. Ten closings that are of different durations but average the same as the first case will produce more than 10 times the total delay. This is because the delay function is non-linear in duration: adding a minute of duration increases delay by more than the amount that is saved by subtracting a minute. The naive model of using the average duration to estimate total delay creates a bias.

### 1.2.3 Averages of Bivariate Distributions

The cost of a crash is both an accounting element based on empirical data and an abstract statistical construct. For a single event (one crash) the impacts can be measured or estimated, dollar values placed on the impacts, and the various cost estimates summed. No two crashes are the same, however, nor have the same consequences, so each crash has a different cost.

The cost of a "representative" crash becomes a purely statistical artifact, as does any calculation of an average. If the result is used for such purposes as placing a monetary value on a crash avoided, or a number of crashes avoided, then the calculation of the average must in some way embody the detailed characteristics of the full range of expected crashes. There exists some number that would be the average of all of the crashes under consideration, but there would be no way to calculate that amount without observing all crashes and valuing each one individually.

This question of empirical method underlies the entirety of this report. There is no definitive answer to the question of what is the correct method or the "true" average, and even good answers require myriad compromises between accuracy and feasibility.

### 1.2.4 Fundamental Crash Cost Equation

The need to group crashes into categories that reflect differences in both cost consequences and crash cause leads to a simple equation that is fundamental to crash cost estimation (Figure 8):

$$\text{Total Crash Costs} = \Sigma_i N_i \times C_i$$

**Figure 8. Equation. Fundamental Crash Cost Equation**

Where $N_i$ = number of crashes per year of type $i$,

$C_i$ = average cost of a crash of type $i$.

The range of *i* must encompass all of the types of crashes potentially affected by the regulation without overlap, i.e., the set of crash types must be mutually exclusive and collectively exhaustive. The choice of what constitutes a “type” and how many types are needed depends upon several considerations, such as purpose and data availability.

### 1.2.5 Developing a Crash Typology

The objectives of a good typology are as follows:

- It constitutes a partition of all CMV-involved crashes, meaning that the categories are mutually exclusive and collectively exhaustive. Every crash falls into one and only one category.
- The characteristics that define a category should be important drivers of cost differentials between crashes. Stated differently, the costs per crash for crashes within a category are expected to be much less widely dispersed than the population of crashes as a whole. The purpose is to make the estimates of crash costs more robust than averaging all characteristics into a single category.
- Ideally, the categories are directly or indirectly related to the differential impacts of existing and potential truck safety regulations, such that the impact of a given regulation or policy is dependent upon the types of crashes affected.
- Finally, the categories need to be those that can be adequately supported by existing data and methods or models.

The methods outlined below and explained in greater detail in subsequent chapters attempt to serve these objectives subject to the constraints of data and level of effort.

## 1.3 PROPERTY DAMAGE COSTS

The estimation of property damage was accomplished by obtaining data from a trade organization that collects data from insurers providing coverage to carriers and then aggregates the data to ensure that no information about individual insurers or carriers is revealed.

The only problem with these data was the omission of damages that were less than the amount of the policy deductible. A method was developed for un-biasing the data for data truncation, and the results are described in Section 2.

## 1.4 FUNCTIONAL LINKAGES FOR INCIDENT DELAY

Delay from crashes is a substantial social cost of crashes, and closely tied to excess emissions of pollutants. No direct data describe crash incident delay, so available data needed to be linked and transformed in ways that could yield plausible estimates of delay. The series of functional linkages that allows delay to be estimated from applicable data are identified in Figure 9.

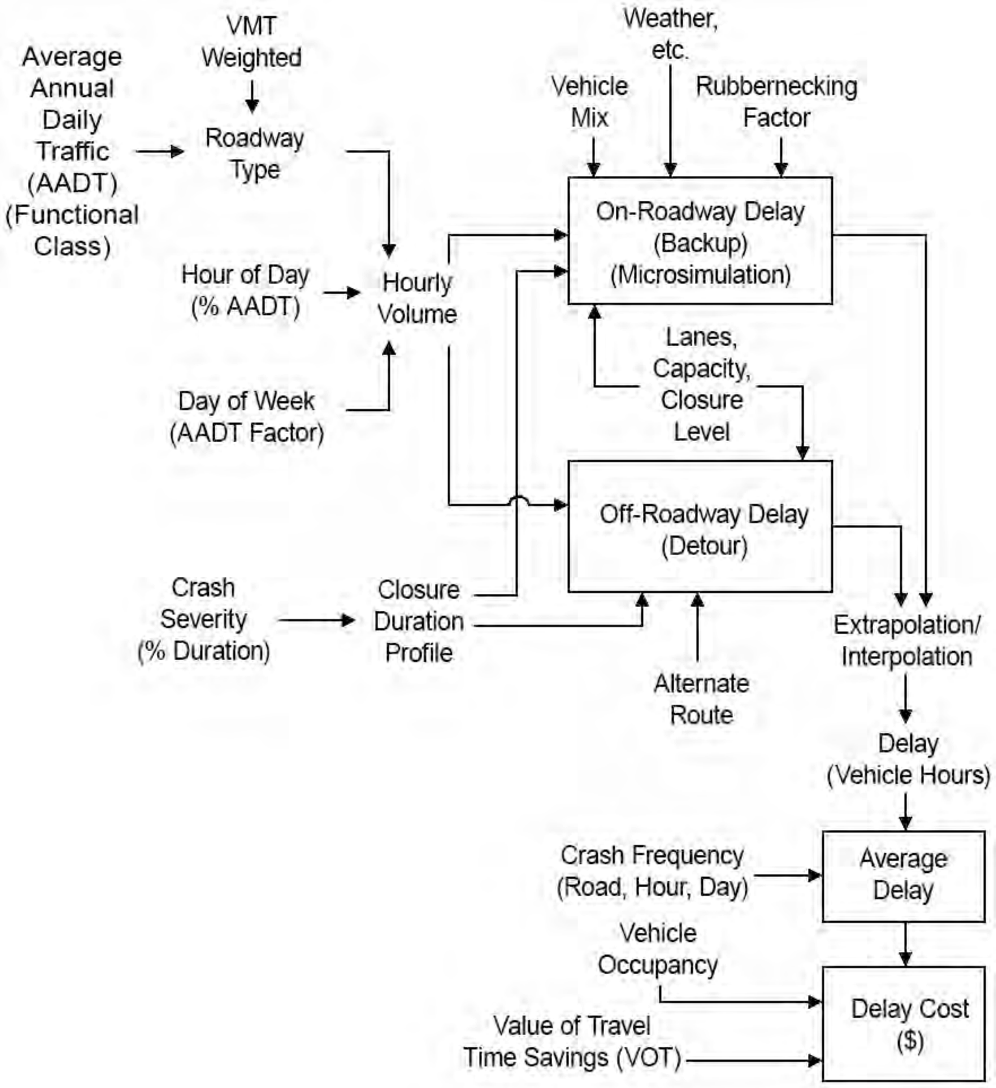


**Figure 9. Schematic Outline for Estimation of Delay Cost per Crash**

### 1.4.1 Average Annual Daily Traffic (AADT) Volume

AADT volume for each of the five roadway types used in this study is the weighted average volume for the functional class taken from HPMS and also used in FARS. Weekday and weekend daily volumes are factored from the same empirical data used for hourly volume, for each roadway type (as shown in Table 20).

### 1.4.2 Roadway Types

The analysis differentiates delay estimates by roadway type for several reasons:

- To limit the range of typical volumes (e.g., high-volume roads versus low-volume).
- To distinguish between the impacts of regulations that may have a focused impact, such as rural interstates.

- To acknowledge the differences between road types in both frequency and severity of crashes (e.g., low-speed local roads versus expressways).

The road types selected for estimating delay from crashes are combinations of standard functional classes. These purposes can be served by using five roadway types, meaning that the balance between different characteristics of different roads versus homogeneity within types is reasonable. The five roadway types are as follows:

- Urban Interstate/Expressways.
- Urban Arterial.
- Urban Other.
- Rural Interstate/Principal Arterial.
- Rural.

These types are aggregations of FHWA functional classes, as shown in Table 11 and described below in generic terms.

#### *1.4.2.1 Interstates and Other Highways*

This category comprises the designated Interstates and other expressways in the U.S. high-capacity network. Interstate highways are divided with full control of access and have two or more lanes in each direction. This classification also includes freeways and expressways that are not part of the Interstate Highway System. Freeways and expressways are defined as divided facilities with either full or partial control of access and with two or more lanes in each direction. Speed limits on interstate highways fall between 55 and 75 miles per hour (mi/h). (The speed limit is 80 mi/h on some highway segments in Texas and Utah [Insurance Institute for Highway Safety]).

#### *1.4.2.2 Major and Minor Arterials*

This classification includes Other Principal Arterials (i.e., Interstate Highways, Freeways and Expressways). Major Arterials connect major cities and population centers. Unlike interstate highways, freeways and expressways, these roads do not have controlled access and may or may not have signalized intersections. According to the Massachusetts Office of Transportation, the posted speed limit on these roads can vary between 25 and 55 mi/h. Minor Arterials interconnect the Principal Arterial system with lower functional highway categories. These roads also have posted speed limits between 25 and 55 mi/h.

#### *1.4.2.3 Local Roads*

Rural and urban local roads and streets are included in the “Other” categories. Only a small share of heavy truck traffic is carried on these roads, and speeds are generally less than 35 mi/h.

### 1.4.3 Hourly Volume

Shares of daily volume by hour and by day of the week are extracted from automatic traffic recorder (ATR) data from a representative set of stations maintained by States and provided to

FHWA. These data have recently been made available to analysts. After data reduction and numerous comparisons, it was decided that weekday and weekend constituted sufficient volume difference by days, and roadway types could be collapsed into four types for daily distributions (see Table 18, Figure 23, and Figure 24).

### 1.4.4 Lanes

The roadway type determines the number of lanes available. The number used for simulation is the VMT-weighted average of lanes in HPMS sections of the given roadway type.

### 1.4.5 Capacity

Full capacity and free-flow speed are determined from the characteristics of the roadway, such as number of lanes and design standard (expressway, arterial, local).

### 1.4.6 Closure Level

Closure level is a discrete attribute of a crash: full, partial, or none. Even if a crash results in no closure (and zero duration), the presence of the crash creates a slowdown due to rubbernecking. Depending upon the total number of lanes and how many are blocked, the simulation reduces the capacity by an empirically determined factor (as shown in Table 25).

### 1.4.7 Crash Severity

CMV crashes are characterized by three levels of severity (fatal, injury only, and property damage only [PDO]) and by five roadway types. A person injured in a crash who dies within 30 days of the crash is recorded as a fatality. GES provides the five-tier KABCO (a scale of crash severity ranging from fatality to PDO) score (Table 9) which is compressed to the three-level severity categories of Fatal, Injury, or PDO. The Motor Carrier Management Information System (MCMIS) dataset allows for positive identification of either fatalities or injuries at a crash site, and if neither of these occur, then the crash is be presumed to be PDO if the crash meets at least the definition of a towaway crash (GES includes non-towaway crashes).

**Table 9. KABCO Crash Severity Scale**

| Crash Severity (KABCO) | Model Severity Category |
|---|---|
| (K) Fatal | Fatal |
| (A) Incapacitating Injury | Injury only |
| (B) Non-Incapacitating Injury | Injury only |
| (C) Possible Injury | Injury only |
| (O) PDO | PDO |

### 1.4.8 Closure Duration

The length of time that the road is closed after the crash is determined by the severity, in three levels: fatal crash, injury crash, or PDO crash. This does not set the absolute number of minutes for the closure but, rather, the frequency distribution of crashes across half-a-dozen discrete duration bins (plus zero). Each of these bins is then subsequently modeled (as shown in Table 29).

### 1.4.9 Duration Profile

An assumption is that after a crash occurs, highway or other relevant police officers will take appropriate actions. These actions are stated as a set of rules that are differentiated by roadway type (i.e., capacity and location). The profile is specified in two phases, on the roadway before diversion occurs, and off the roadway after traffic is diverted. The trigger for duration may be time (0.75 hours, 1 hour) or backup length (0.25 miles, 1 mile), depending on the roadway type (as shown in Table 26).

### 1.4.10 Vehicle Mix

The mix of vehicle types (cars, trucks) in the traffic stream affects the amount of delay and its opportunity cost in the microsimulations. Vehicle mix by straight truck, combination truck, and passenger vehicles is taken from HPMS.

### 1.4.11 On-Roadway Delay

Microsimulation modeling is applied to a range of crash scenarios (roadway type, volume, duration, and closure degree) and other parameters specific to the simulation to generate backups. These Monte Carlo simulations[6] apply to the roadway itself and immediately adjacent roads, and produce on-the-roadway delay for a single crash (as shown in Table 27). At some designated backup length or duration, traffic is diverted to other roadways.

### 1.4.12 Diversion Detour Modeling

Off-the-roadway or network modeling is in the form of a deterministic queuing model specific to each roadway type. The model accepts data on access to an alternate route, along with its capacity, speed, and length. This delay is added to the on-the-roadway delay (as shown in Table 26).

### 1.4.13 Extrapolation and Interpolation

The output of the combined simulations is total delay for a given set of parameters. Not all combinations can be simulated due simply to the enormous number that would be required. Instead, a three-dimensional surface was fitted to the data generated by the simulations. This allowed the delay estimation to be interpolated to points (parameter combinations) not explicitly modeled and to extrapolate delay to points for which there are no data (as shown in Table 28).).

### 1.4.14 Crash Frequency

Results for each type of CMV crash are expanded to a single representative or “typical” or average crash for the population as a whole by means of “weights” applied to each category. Average delay for a generic crash prevented, for example, would be the delay arising from the specific conditions chosen to represent each type of crash (e.g., fatal urban expressway crashes), times the frequency for the crash type, summed over all relevant types.

Crash frequencies are obtained from several data sources described below. The FARS dataset is used for fatal crashes because it tabulates all fatalities and tabulates them by functional class. The GES dataset is used for all non-fatal crashes because it covers all crashes, although the

---

[6] Monte Carlo simulations use random variables (usually within a defined range) to create a variety of possibilities for analysis.

assignment to road type requires using a combination of characteristics to approximate road types (as shown in Table 30).

### 1.4.15 Dollar Valuation

Valuation of delay time is a result of multiplying delay hours by the applicable value of travel time savings (VOT) (as shown in Table 35). Valuation of environmental impacts draws on unit cost parameters published by the Environmental Protection Agency (EPA).

These parameters can be updated and new results easily obtained without re-doing the calculations needed to estimate the quantities of delay time and pollutant emissions.

### 1.4.16 Data Integration

The raw data used to design and power the various models have been frequently referred to above, but a comprehensive view of which data feed which models has not been displayed. Before describing the data sources in more detail, it will be helpful to summarize the content of the information extracted from each database. Figure 10 is a flow chart that identifies the ties from the data sources to the major intermediate variables they support. These connections are made to the analytic components shown in Figure 11.

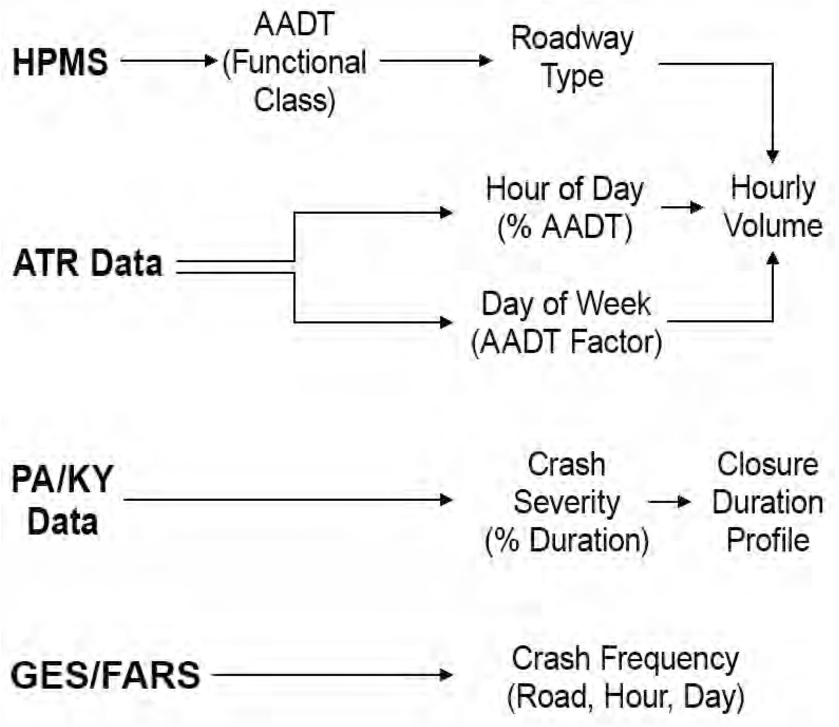


Figure 10. Primary Data Sources and Inputs

Hourly traffic volume and crash duration are the primary drivers for the delay simulation models, creating a three-dimensional surface of delay as a function of the two inputs. The simulations generate points on this surface, from which a sigmoidal surface is constructed statistically to fill in the combinations that were too numerous to model individually.

The crash frequency distributions are then applied to the complete set of points to calculate the expected value of the bivariate function, which is the average crash cost for the conditions stated.

### 1.4.17 Failed Relationships

Several other factors known or hypothesized to affect crash frequency, severity, or cost were considered but not used for empirical estimation. The study concluded that any method for attempting to incorporate these effects would be just as likely to add error as to increase precision.

Figure 11 shows schematically many of the factors hypothesized to affect those crash costs under consideration in this report. For example, vehicle type, day of the week, and severity of the crash are thought to be possible factors influencing the duration of closure, but only severity was actually used. Neither data nor theory were strong enough to establish any of the functional relationships represented by a gray line in the diagram.

Other possible variables that were considered are shown in Table 10. Either the data were inadequate to establish or calibrate a relationship, or no theoretical rationale was sufficiently persuasive to defend a relationship.

The option to characterize crashes by vehicle type was considered but abandoned after finding that vehicle type was not an important factor in predicting the impacts of the crash on other roadway users. Vehicle type may affect the severity of a crash, but once one has accounted for severity, the vehicle type has only negligible effects on the duration of a road closure after a crash. In addition, the data available to measure the additional effect of truck type on delay was not plentiful enough to investigate both severity and truck type simultaneously. Section 3 provides more details on this investigation.

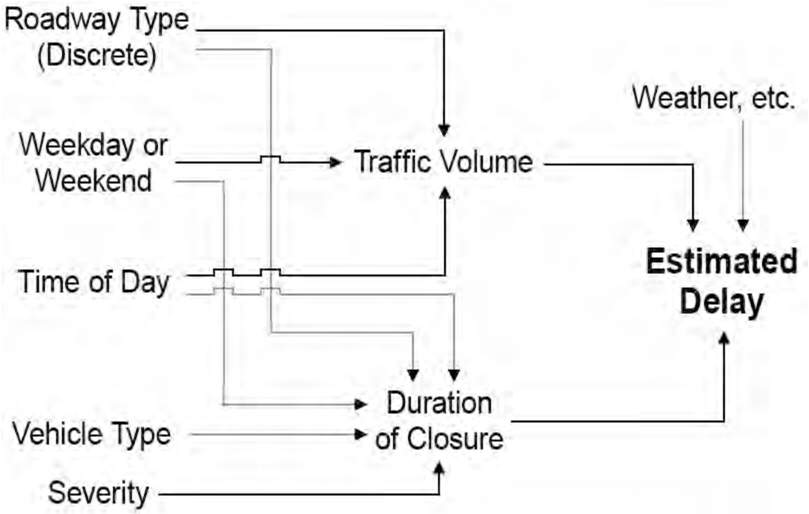


Figure 11. Omitted Factors Potentially Affecting Crash Costs

**Table 10. Variables Omitted from Delay Modeling**

| | |
|---|---|
| **Weather** | Rain, snow, fog, high winds, temperature and other weather conditions can both increase the frequency and the severity of crashes, and also the duration of the associated incident. Weather may also complicate the costs of cleanup. Weather affects emissions and is included as a factor for environmental costs. |
| **Terrain** | Topography is classified for highway purposes in the HPMS as flat, rolling, and mountainous. These categories pertain mainly to rural sections where incident volumes are generally modest. |
| **Megacrashes** | An ideal crash typology shows relatively finer-grain detail for crashes with large costs, whereas crashes with minor impacts beyond the vehicles and persons involved can be aggregated across road types and other dimensional categories. Megacrashes are a small share of the total, but potentially very large in terms of damages and costs. The conclusion was that such crashes are encompassed within the range of conditions (roadway type, traffic volume, location) represented in the simulations. |

## 1.5 EMISSIONS AND VEHICLE OPERATING COSTS

Data were extracted from the simulations in the incident delay procedures and transformed into inputs to the MOVES emission modeling software. Simplified relationships were also developed for extrapolating functional relationships to diverted traffic as well.

Output quantities in tons of pollutants were valued using EPA estimates of unit costs. The methods and results are described in Section 4. Emissions from motor fuel tank leakage as a result of collisions are also estimated.

Additional fuel consumption caused by delay is estimated from the microsimulation model (TSIS-CORSIM) and the MOVES emissions models. Other vehicle operating costs that might be affected by crash incidents, such as tire wear, vehicle wear, vehicle maintenance, and battery life have not been estimated.

## 1.6 DAMAGES FROM HM CRASHES

A final section provides a separate framework and methods for estimating costs from crashes that involve a HM spill. HM crashes are included in the data used to estimate the general costs of CMV crashes, but they are a small share of total crashes. If there is a need to estimate the costs of hazardous spill crashes alone, then this section contains a methodology for that purpose.

There are separate data that allow for independent estimates of HM crash costs, if attention is limited to that sector of the trucking industry. Methods, data, and results are provided in Section 5.

## 1.7 CRASH FREQUENCY, SEVERITY, AND DURATION DATA

Three publicly available datasets can be used for investigating U.S. truck crash characteristics and frequencies. These datasets are maintained by the U.S. Department of Transportation and contain crash specific information such as roadway characteristics, severity of crash, time of day, and day of week.

The following section describes the database’s crash-specific information for U.S. CMV crashes and discusses which databases were selected as the basis for modeling the truck crashes. The type of information available to describe each crash is then discussed.

### 1.7.1 Data Sources

The five crash databases examined for the truck crash model are described below:

- **Fatality Analysis Reporting System (FARS)—**This is a census of all fatal crashes on the U.S. Highway System. The FARS database is maintained by the National Highway Traffic Safety Administration (NHTSA).
- **General Estimates System (GES)—**This database contains a nationally representative probability sample taken from an estimated 6 million annual crashes. It details all crashes on the U.S. Highway System. Sample crash information extracted from this database can be expanded to represent national totals. This database is maintained by NHTSA.
- **Motor Carrier Management Information System (MCMIS)—**This database is maintained by FMCSA. It contains information on Federally recorded truck crashes as reported to FMCSA by states using state police crash reports. Some of the information in MCMIS is culled from the FARS database. Crashes are reported only if a vehicle was towed from the scene due to disabling damage.
- **Automatic Traffic Recorder (ATR) Data (FHWA)—**A large volume of data has been made available by states through FHWA based on 24-hour counts at numerous ATR stations on all types of roads (data not readily available to the public).
- **Selected State Data—**Incident truck crash data were obtained from Kentucky, Pennsylvania, and Washington from which the distribution of crash closure durations by severity level were extracted (data not readily available to the public).

### 1.7.2 Data Extraction

Directly matching crash information across the first three databases listed above is not possible due to the differences in how they are constructed. The GES database represents a sample of all nationwide crashes at all severities, while the FARS database is a census of only fatalities. The MCMIS database, on the other hand, includes a count of Federally reported truck and bus crashes that are passed along to FMCSA by States. Further, a crash is only reported in MCMIS if it resulted in a fatality, injury, or towaway vehicle.

For purposes of analyzing truck crashes, it is therefore necessary to determine the most comprehensive and useful sources of crash data. For fatal crashes the obvious source is the FARS database, which represents a census. For non-fatal crashes, however, data could be extracted from either GES or MCMIS. Note that in MCMIS, an injury crash requires the victim to be transported from the scene for medical treatment. Queries of the GES and MCMIS datasets showed that MCMIS had records for far fewer crashes than GES due in part to the requirement for reporting only fatalities, injury, and towaway crashes in MCMIS. As comprehensiveness was the goal, this analysis uses data from GES for non-fatal crashes.

The present study focuses on just CMV crashes, and these data sources contain data on all crashes (including passenger vehicles). CMV crash records are defined as those where at least one of the vehicles involved in the crash is a bus (i.e., charter and intercity), a single unit straight truck, a tractor-trailer (i.e., cab only, or with any number of trailer units), or unknown medium/heavy truck type.

### 1.7.3 Roadway Type

The type of roadway where the crash occurs is an important component in the determination of traffic delays as a result of a crash. For example, a crash on a high volume interstate highway in an urban area would be expected to have a different delay pattern than a crash on a less densely traveled interstate highway in a rural area.

The functional classification definitions used in the collection of HPMS traffic volume data by the Federal Highway Administration (FHWA) form the starting point for building the classifications used for analyzing crash data.

### 1.7.4 FARS Database

The FARS dataset contains all of the HPMS functional classifications. FARS also makes a clear distinction between roads in rural and urban areas. The relationship between the HPMS functional classifications and the roadway types used for this report is shown in Table 11.

**Table 11. FHWA/FARS Functional Classes**

| Roadway Type/Facility Type | HPMS/FARS Classification |
|---|---|
| Urban Interstate/Expressway | Urban Principal Arterial—Interstate<br>Urban Principal Arterial—Other Freeways or Expressways |
| Urban Arterial | Urban Other Principal Arterial<br>Urban Minor Arterial |
| Urban Other | Urban Local Road or Street |
| Rural Interstate/Principal Arterial | Rural Principal Arterial—Interstate<br>Rural Principal Arterial—Other |
| Rural Other | Rural Minor Arterial Rural Major Collector<br>Rural Minor Collector<br>Rural Local Road or Street |

### 1.7.5 GES Database

While the GES does not contain specific HPMS functional classifications, it does contain many descriptors of the roadway where the crash occurs. These descriptors include an indicator variable for whether the roadway is part of the Interstate highway system, the speed limit of the roadway, the number of lanes of the roadway, and whether the roadway is divided or not. The descriptors are used to impute a roadway type for the crash. The HPMS database was queried to determine which functional classification was most probable (on a vehicle miles basis) for a roadway with certain classifications. For instance, the HPMS shows that 82 percent (on a vehicle miles traveled basis) of rural roads with two lanes and speed limits less than or equal to 45 mi/h are Rural Major Collectors. A roadway with those characteristics is modeled as "Rural Other" for the purposes of this report. The classification rules used for GES crashes are shown in Table 12 (the GES database often lacks information on the number of lanes of the roadway where the crash occurs. Separate classifications are developed for crashes when information on the number of lanes is missing).

The GES Interstate descriptor is defined in the coding manual as "those trafficways that are within the national system for interstate transport and defense purposes. Interstates typically have limited access and multiple lanes of travel." Crashes that occur at on or off ramps of an interstate highway are also classified as being on an interstate highway. The GES manual notes that this definition does not include crashes that occur on U.S. highways, State highways, county roads, township roads or municipal roads.

**Table 12. GES Road Classifications**

| Roadway Type | GES Identification |
|---|---|
| Urban Interstate/Expressway | Interstate or speed limit 55 mi/h or higher with four or more lanes. |
| Urban Arterial | Non-interstates that are four or more lanes and less than 55 mi/h. |
| Urban Other | Non-interstates with fewer than four lanes. |
| Rural Interstate/Principal Arterial | Interstate or four or more lanes. |
| Rural Other | Non-interstate with fewer than four lanes. |

The GES database does not have a direct classification that separates out urban or rural highways. Rather, it identifies the land use, in terms of population, which is associated with the jurisdiction of the police officer who recorded the accident. The categories are as follows:

- Within area of population 25,000–50,000.
- Within area of population 50,000–100,000.
- Within area of population more than 100,000.
- Other Area.
- Unknown.

For the GES crashes, an area with a population less than 25,000 is categorized with rural functional classifications for the purposes of this crash cost model (these are identified using the Other Area and Unknown fields in the GES database), while areas with a population 25,000 and above are considered to be urban areas. This definition varies somewhat from the classifications in the FARS database which is based on the HPMS database. The HPMS classifies any area with a population greater than 5,000 as an urban area.

The above classification schemes leave some crashes unattributed to a roadway type. Approximately 28 percent of crashes across 3 years in the GES are unallocated using the above classification. Approximately 0.5 percent of crashes in FARS were unallocated. The unallocated crashes in FARS represent a small minority of crashes and will not affect the overall distribution. However, the unallocated crashes in GES must be addressed.

In the GES, the majority of the unallocated crashes were missing information on the number of lanes, but the urban/rural item was available. The unallocated crashes were first split into urban and rural categories, then allocated according to 2008 VMT in those categories. The resulting final distribution is presented in Table 13. The numbers presented are annual average number of crashes for 2006–08.

**Table 13. Average Annual Crashes by Roadway Type and Severity (Based on 2006–08 GES Data)**

| Roadway Type | Fatal | Injury | PDO | Total |
|---|---|---|---|---|
| Rural Interstate/Principal Arterials | 1,434 | 18,907 | 56,391 | 76,713 |
| Rural Other | 1,207 | 15,441 | 48,504 | 65,133 |
| Urban Interstate/Expressway | 627 | 13,639 | 66,351 | 80,602 |
| Urban Arterial | 464 | 15,699 | 74,621 | 90,742 |
| Urban Other | 526 | 13,056 | 75,312 | 88,839 |
| **Total** | **4,259** | **76,743** | **321,178** | **402,180** |

### 1.7.6 MCMIS Database

The MCMIS database does not provide direct information on the functional classification for the highway on which a crash occurs. The database has a variable titled “trafficway,” which provides information on whether a road is divided or not under the following categories:

- Two-way trafficway, not divided.
- Two-way trafficway, divided, unprotected median.
- Two-way trafficway, divided, positive barrier.
- One-way trafficway, not divided.

Along with the trafficway variable, MCMIS has information on the access to a roadway. There are three classifications in this category as follows:

- Full control (entry and exit ramp access such as an interstate highway).

- Partial access control (mixed).
- No control (no control of entry and exit traffic to the road).

Combining these two variables allows for estimating whether a crash took place on a certain type of road. For example, combining two-way traffic and positive barrier with full control access would represent a Principal Arterial such as an interstate highway, freeway, or expressway. The MCMIS dataset also has an entry for the city, State and county for each crash. While indirect, it was possible to separate crashes into rural and urban based on these variables.

### 1.7.7 State Crash Data

The data sources described above all lack an essential measure, namely, the duration of individual crashes, or the distribution of durations for a category of crashes. To fill this gap, three States offered to provide the data they had collected and tabulated on crash characteristics. Two of the States—Pennsylvania and Kentucky—had data covering the full range of roadway types, and their data were merged to construct frequency distributions of incident duration (the period of time during which the road is partially or fully closed) by severity. The data necessitated the usage of a given set of "bins" for duration (e.g., 30–60 minutes). No other tabulations (e.g., duration by roadway type, traffic volume, or vehicle type) were statistically feasible.

These data clearly have limitations. The frequency distribution of crash types may differ among States, and the State and local police policies for dealing with incidents may affect crash duration. The data are not numerous and can be affected by rare events. A potential source of improvement for future estimates of CMV-involved crashes would be deeper and more granular data on the distribution of incident duration times.

[This page intentionally left blank]

# 2. PROPERTY DAMAGE COSTS

This section presents estimates of average property damage costs stemming from truck crashes. The primary source of data for this analysis comes from the ISO, a company that collects detailed information on truck insurance liability and collision property damage claims. The ISO data were drawn from claims filed in 2008 and include aggregate average collision and liability property damage claims, the variance of collision claims, and deductible information, for nearly 80 percent of insured motor carriers nationwide.[7] Given a few caveats described in greater detail below, these data are assumed to provide a proxy measure of the internal and external property damage costs associated with a crash.

The mean value of property damage resulting from a crash includes damage to the motor carrier and damage to other vehicles[8] or structures involved in the crash. Using insurance data, collision claims serve as a proxy for damage to the motor carrier and liability claims serve a proxy for damage to others. Thus, the relationship between crash costs and insurance claims is described in Figure 12:

$$\text{Mean Property Damage Cost} = \overline{C} + \overline{L} \times N$$

$$\begin{aligned} \text{where}\quad & \overline{C} = \text{the average collision claim amount,} \\ & \overline{L} = \text{the average property damage liability amount, and} \\ & N = \text{the average number of other vehicles involved in a truck crash.} \end{aligned}$$

**Figure 12. Equation. Relationship between Crash Costs and Insurance Claims**

For the most part, this methodology follows that of Zaloshnja and Miller (2004), but corrects for potentially serious data truncation issues inherent in the insurance data. The problem of data truncation arises because a (potentially) large number of small crashes may not result in a motor carrier filing a collision insurance claim, especially if the cost of the damage is less than the policy deductible. The text below describes the nature of the problem in greater detail and presents a statistical correction procedure. The corrected property damage cost estimates are presented for a variety of truck sizes.

## 2.1 DATA TRUNCATION

In many instances, researchers would like to make statistical inferences about a population when the sample of observed data is drawn from a subset of that population. If the sample is restricted such that the variable of interest is only observed above some threshold, the data are said to be left-truncated. This characteristic of the observed data makes it challenging to estimate descriptive statistics such as the mean or variance of the full, untruncated population. Without correcting for data truncation, estimates of population means and variances will be biased. If truncation is from below, the sample mean will exceed the population mean by an amount proportional to the degree of truncation (i.e., the amount of observations below the truncation threshold). For the current analysis, the goal is to estimate the mean cost of crash-related

---

[7] The data cover every state except for Massachusetts, but tend to underrepresent small insurance providers. The resulting analysis assumes that the behavior of motor carriers does not systematically differ by the size of their insurer.

[8] The number of other vehicles involved in a truck crash was drawn from the 2008 GES.

property damage to at-fault truck drivers. To generate this estimate, data from collision insurance claims and property damage liability insurance claims were used. However, the only truck crashes that will generate a collision claim are those for which the amount of damages exceeds the insurance policy's deductible. In this context the data are left-truncated, and the truncated sample mean may not be a useful indicator of the population mean of interest (i.e., average crash costs). Figure 13 illustrates how the distribution of collision claims (the available data) compares to the distribution of crash costs borne by an at-fault motor carrier (the statistic of interest).

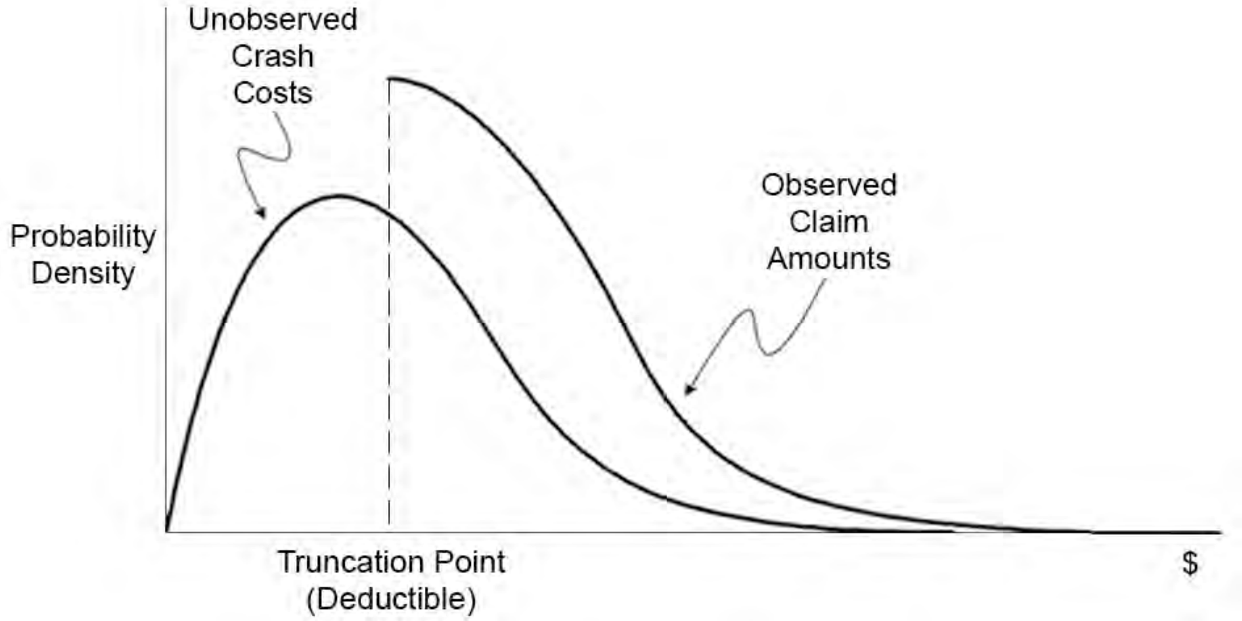


**Figure 13. Truncated Distribution Versus Complete Distribution**

In general, correcting for data truncation is not a difficult task. With individual collision claim amounts, the associated truncation thresholds (i.e., policy-specific deductibles), and a distributional assumption, the method of maximum likelihood will generate minimum-variance unbiased estimates. That estimator is easy to implement, can account for observation-specific thresholds, and can be extended to estimate conditional expected values (i.e., the regression approach). However, only a limited set of information about truck insurance claims is available. That is, it was only possible to obtain related summary statistics including the mean and variance of liability claims for different truck types, but not the underlying sample of data points. In this case, the approach to dealing with truncation becomes somewhat more complicated. To address that shortcoming, this section presents a solution to the truncation problem when one only knows the mean, variance, and mean threshold of a left-truncated distribution. The approach presented here is known as the method of moments, and is shown to be a feasible technique for dealing with left truncation when the random variable of interest is distributed lognormal, which is a reasonable assumption for truck crash costs.

## 2.2 ESTIMATION

### 2.2.1 Method of Moments

The method of moments is a technique that can be used to estimate the unknown parameters of the underlying distribution of a random variable (in this case property damage costs). The idea behind the method of moment's estimator is straightforward, and involves equating the moment expressions that characterize a distribution to their sample counterparts, and solving the system of equations for the unknown parameters.[9] In general, more than one parameter describes the distribution of a random variable and its moments. So, in order to apply the method of moments, the system just described will include just as many equations as there are unknown parameters. In the case examined here, a truncated log-normally distributed random variable is characterized by two parameters, *mu* (centrality) and *sigma* (spread). The first truncated moment expression of the lognormal distribution (presented in log-form) is:

$$m_1(\mu,\sigma) = \mu + \ln\left(1 - \varphi\left(\frac{\ln(\bar{d}) - \mu - \sigma^2}{\sigma}\right)\right) - \ln\left(1 - \varphi\left(\frac{\ln(\bar{d}) - \mu}{\sigma}\right)\right)$$

**Figure 14. Equation. First Truncated Moment Expression of the Lognormal Distribution**

and the second truncated moment expression is:

$$m_2(\mu,\sigma) = 2\mu + 2\sigma^2 + \ln\left(1 - \varphi\left(\frac{\ln(\bar{d}) - \mu - \sigma^2}{\sigma}\right)\right) - \ln\left(1 - \varphi\left(\frac{\ln(\bar{d}) - \mu}{\sigma}\right)\right)$$

**Figure 15. Equation. Second Truncated Moment Expression of the Lognormal Distribution**

where *phi*( ) is the normal cumulative distribution functions and *d bar* is the mean truncation point.

Estimating the unknown parameters of interest (*mu* and *sigma*) requires solving a system of two equations in two unknowns. The expressions that equate the first and second moment expressions to the sample mean (theta overbrace subscript 1) and sample uncentered second moment (theta overbrace subscript 2) are:

$$f_1 = \mu + \frac{\sigma^2}{2} + \ln\left(1 - \varphi\left(\frac{\ln(\bar{d}) - \mu - \sigma^2}{\sigma}\right)\right) - \ln\left(1 - \varphi\left(\frac{\ln(\bar{d}) - \mu}{\sigma}\right)\right) - \ln(\widehat{\theta}_1)$$

$$f_2 = 2\mu + 2\sigma^2 + \ln\left(1 - \varphi\left(\frac{\ln(\bar{d}) - \mu - \sigma^2}{\sigma}\right)\right) - \ln\left(1 - \varphi\left(\frac{\ln(\bar{d}) - \mu}{\sigma}\right)\right) - \ln(\widehat{\theta}_1)$$

**Figure 16. Equation. Expressions That Equate the First and Second Moment Expressions to the Sample Mean and Sample Uncentered Second Moment**

---

[9] See Greene (2003), Econometric Analysis, pages 526-533 for an overview of the method of moments estimator.

Note that the system is in log-form and that *f* subscript 1 and *f* subscript 2 are implicit functions, as *mu* and *sigma* are not separable.

## 2.3 NEWTON-RAPHSON ALGORITHM

Using the first and second truncated moment expressions, the stage is set to estimate the parameters *mu* and *sigma*, which can be used to estimate the untruncated mean of interest. The expressions in Figure 16 highlight a significant hurdle: there is no analytic solution to the method of moments system of equations. This hurdle arises because there is no closed-form representation of the normal cumulative distribution function. However, a computational solution to the system of equations is feasible, but cumbersome. The algorithm works by linearizing a system around a starting point (the initial guess at the solution) and solving the linearized system to find an approximate solution. That approximate solution serves as the initial guess for the second step of the process, whereby one linearizes and solves the system around the second approximation point. The process proceeds by iteratively linearizing and solving the system around the previous approximate solution. For a system of two equations in two unknowns (*mu* and *sigma*), the iterative formula for the algorithm (in matrix form) is:

$$(\mu,\sigma)_{n+1} = (\mu,\sigma)_n - J[(\mu,\sigma)_n]^{-1} f(\mu,\sigma)_n$$

**Figure 17. Equation. Iterative Formula**

where *n* indexes the iterations of the algorithm, and *f* ( ) is the vector of moment equations.

$$f(\mu,\sigma) = \begin{pmatrix} f_1(\mu,\sigma) \\ f_1(\mu,\sigma) \end{pmatrix} = \begin{pmatrix} \text{first moment equation} \\ \text{second moment equation} \end{pmatrix}$$

**Figure 18. Equation. Vector of Moments**

Also note that *J* is the Jacobian matrix of partial derivatives of *f* with respect to the vector of unknown parameters (*mu* and *sigma*):

$$J[(\mu,\sigma)] = \begin{bmatrix} \frac{\delta f_1(\mu,\sigma)}{\delta} & \frac{\delta f_1(\mu,\sigma)}{\delta} \\ \frac{\delta f_2(\mu,\sigma)}{\delta} & \frac{\delta f_2(\mu,\sigma)}{\delta} \end{bmatrix}$$

**Figure 19. Equation. Jacobian Equation**

The method of moments estimator solves the system of equations *(f1,f2)* above using the Newton-Raphson algorithm.

Note that the Newton-Raphson algorithm is only guaranteed to find the global maximum provided that the function *f* is globally concave. Due to the highly non-linear character of *f* in this example, however, it is imperative to run the algorithm with several starting points to test the algorithm's robustness. Nonetheless, given the fact that the “true” statistics of interest are bounded by zero and the untruncated sample statistics, convergence to a local maximum rather than the true root is unlikely. This procedure was implemented in the business analytic software SAS, and the source code is available upon request.[10]

## 2.4 STATISTICAL RESULTS

Using the above methodology along with the ISO data for 2008, the average collision claim amounts for a variety of truck sizes are presented in Table 14. Truncated data do not include costs of crashes that are below the insurance deductible and therefore do not usually generate an insurance claim. The corrected data takes into account these lower cost crashes.

**Table 14. Truncated and Untruncated Mean Collision Claims by Truck Type**

| Truck Type | Truncated Mean | Corrected Mean | Percent Difference |
|---|---:|---:|---:|
| Medium Trucks | $7,028 | $6,750 | 4.0% |
| Heavy Trucks | $10,962 | $10,669 | 2.7% |
| Heavy Trucks—Tractors | $12,888 | $12,693 | 1.5% |
| Extra Heavy Trucks | $20,899 | $20,864 | 0.2% |
| Extra Heavy Trucks—Tractors | $16,906 | $16,853 | 0.3% |
| **Total*** | **$11,711** | **$11,505** | **2.4%** |

*Total represents a weighted average, where the weights are the claim frequencies across truck types. Figures are in 2010 dollars.

The truck size definitions are as follows:

- Medium Trucks: gross vehicle weight 10,001–20,000 lbs.
- Heavy Trucks: gross vehicle weight 20,001–45,000 lbs.
- Extra Heavy Trucks: gross vehicle weight greater than 45,000 lbs.
- Heavy Trucks—Tractors: tractor-trailer with gross combined weight less than 45,000 lbs.
- Extra Heavy Trucks—Tractors: tractor-trailer with gross combined weight greater than 45,000 lbs.

The results indicate that costs borne by at-fault truck drivers generally increase with the size of the truck involved in the crash, and range from approximately $6,800 for medium trucks to $20,900 for extra-heavy trucks. Also, note that the corrected means are less than 4 percent different than the truncated means, indicating that the insurance data tend to overestimate property damage costs by a small but significant amount.

---

[10] The performance of the method of moments estimator was tested using simulated data that had characteristics similar to the ISO data. The results indicated that Newton's Method performed well and successfully produced parameter estimates close in magnitude to those used to simulate the data.

The average total property damage cost of a truck crash can be obtained using the Equation shown in Figure 11, the corrected values from Table 14, the mean liability property damage claim amounts from ISO, and the number of other vehicles involved in accident from GES. Table 15 presents the resulting property damage costs by truck type. Note that total crash costs are greatest for extra-heavy trucks because both collision claims and liability claims tend to increase with truck size. The total mean damage cost ranges from approximately $9,700 for medium trucks to $25,300 for extra-heavy trucks.

**Table 15. Estimated Property Damage Amounts by Truck Type**

|  | Mean Collision Claim | Mean Liability Claim | Number of Other Vehicles in Crash | Total Mean Damage Cost |
|---|---:|---:|---:|---:|
| Medium Trucks | $6,750 | $3,738 | 0.8 | $9,740 |
| Heavy Trucks | $10,669 | $4,291 | 0.8 | $14,102 |
| Heavy Trucks—Tractors | $12,693 | $6,081 | 0.8 | $17,558 |
| Extra Heavy Trucks | $20,864 | $5,486 | 0.8 | $25,253 |
| Extra Heavy Trucks—Tractors | $16,853 | $6,178 | 0.8 | $21,795 |
| **Total** | **$11,505** | **$4,683** | **0.8** | **$15,252** |

One cannot directly compare the current results to those of Zaloshnja and Miller (2004), because their results are aggregated into different truck categories and because they failed to correct for data truncation. Their average property damage cost (inflated to 2010 dollars) across all truck categories was reported to be $7,642 in Zaloshnja and Miller (2004).

# 3. INCIDENT DELAY COSTS

Delay consists of the extra or additional time spent traveling that is experienced by vehicle operators and passengers as a consequence of a crash. This extra time would not have been incurred if the crash had not occurred. Incident delay results primarily from road blockage, but the methods used here also allow for delay due to so called “rubbernecking” where drivers slow down out of caution or to view a crash scene.

## 3.1 COST-OF-DELAY MODEL

Estimation of expected delay costs for a representative or typical crash by roadway type and severity is accomplished by a combination of microsimulation analyses for prototype conditions, supplemented with deterministic interpolations and extrapolations. The resulting estimates from different scenarios are weighted by their prevalence to produce an expected delay cost of a CMV crash.

### 3.1.1 Representative or Typical Crashes

A CMV crash can have a wide range of consequences, from a minor “fender bender” to a megacrash involving fatalities and infrastructure damage. In this context the concept of an “average” crash is not very meaningful because the average of all crashes is not the result of the average of all conditions for that category. Because of numerous nonlinearities, conditions that are worse than average generate higher deviations from average cost than do better-than-average conditions generate lower cost deviations. In other words, the distribution of crash costs around average crash conditions is not symmetrical.

Rather than develop an estimate of the costs of an “average” crash, this analysis develops a set of representative or prototype crashes that groups crashes of similar cost magnitude. There will inevitably be significant error in this process, but it is better than trying to estimate a single “average” crash that doesn’t recognize, for example, that traffic volumes vary systematically over types of roads.

This analysis groups crashes into a multi-dimensional matrix. The dimensions are crash severity (fatality, injury, PDO) and roadway type (Urban Interstates/expressways, Urban Arterials, Urban Other, Rural Interstates/Principal Arterials, and Rural Other). Traffic volumes are varied in numerous model runs to represent different times of day and days of week. The severity of the crash determines the duration of the road closure.

This analysis uses the following model as the framework for the analysis. Other component models are used to estimate elements of this general model. The expected cost of delay for a given roadway type and severity is represented by Figure 20.

$$Delay\ Cost_{i,s} = Delay\ Vehicle\ Hours_{i,s} \times Occupancy_{i,s} \times VOT_{i,s}$$

**Figure 20. Equation. Formula to Determine Delay Cost**

Where *i* indexes the five roadway types,
*s* indexes the three severity levels,
and *VOT* = average value of travel time.

VOT represents the individual's value of travel time, which, along with average vehicle occupancy, provides the dollar valuation of the vehicle hours of delay. The results of this analysis are presented in a manner so that these two parameters can be easily updated in the future. The vehicle delay hours per crash will change more gradually, and is more work to recalculate. The methods for estimating occupancy and value of time are illustrated in the following sections.

The average or expected delay hours from all crashes can then be represented by:

$$E(\text{Delay Vehicle Hours}_s) = \Sigma_i \Sigma_t \Sigma_h delay(vol_{i,h},\ dur_{t,s}) \times freq(vol_{i,h,s}) \times freq(dur_{t,s})$$

**Figure 21. Equation. Formula to Determine Delay Vehicle Hours**

where *i* indexes the five roadway types,
*s* indexes the severity level of the crash (fatal, injury, PDO, or all crashes),
*h* indexes the 48 hour types (24 weekday hours + 24 weekend hours),
freq($vol_{i,h,s}$) = the severity-specific probability or frequency weight of a crash on road type i in hour type h of severity s,
freq($dur_{t,s}$) = the severity-specific probability of a closure of duration t due to a crash,
delay($vol_{i,h}$, $dur_{t,s}$) = a function that provides vehicle hours of delay for a crash on a given roadway type, traffic volume, severity, and duration of road closure.

Note that the frequency distribution of crashes by volume is independent of the distribution by duration; the data used were insufficient to construct different duration distributions for road types, time of day, or day of week. Duration distributions for severity levels are taken from State-level data.

The modeling strategy is to construct a mathematical function that can provide an estimate of vehicle hours of delay for a given incident when provided with certain key details of the incident, including a description of the roadway, volume of traffic on the roadway, and roadway closure duration. The function is applied to various combinations of those descriptors and the resulting estimates of vehicle delay are assigned probabilistic weights and summed to return an expected value of hours of vehicle delay for a certain severity and roadway type. Finally the vehicle delay is multiplied by average vehicle occupancy rates for that roadway type and the value of time for users of that roadway type to produce a monetized cost of delay for a crash on that roadway type of the specified severity.

The remainder of this section provides details on how each of the components of the equations in Figure 20 and Figure 21 are estimated.

## 3.2 DEVELOPING DESCRIPTORS OF CRASHES

As explained in the previous section, the delay associated with crashes of various types are determined by three main characteristics: characteristics of the roadway, the volume on the roadway at the time of the crash, and the duration of the road closure. The details of specifying each of those parameters are described more fully below.

### 3.2.1 Representing the Roadway

For a given crash, the vehicle hours of delay depend most heavily on the volume of traffic and the duration of the road closure resulting from the crash. Other characteristics of the roadway such as capacity, average speeds, and availability of alternate routes are also important factors. To account for the latter type of characteristics intrinsic to the roadway, a prototypical example of each of five road types was developed for modeling purposes. With a typical roadway environment specified for each roadway type, different simulations are run with varying volumes and durations of road closure.

Within any roadway type there are certainly a variety of characteristics. For instance, the category Urban Interstate/Expressway could be 4 lanes in some areas or up to 16 lanes in a major city like the downtown connector in Atlanta. For the purposes of this model, a single representation for each of the five roadway types is needed. The HPMS database of roadway statistics is used as the basis for developing the needed representations. For each roadway type, the VMT-weighted median number of lanes is shown in Table 16. The average speed, AADT and traffic composition are the VMT-weighted median values for road segments of that roadway type with the specified number of lanes. The information shown in the table is the basis for the roadway descriptions used in the simulation models.

### 3.2.2 Volume of Traffic

Total delay per crash is expected to be highly non-linear. At most times on most roads, traffic volumes are low to modest, and complete blockage of the roadway does not result in large aggregate vehicle delays, even if the duration of the incident is fairly long. There often are *ad hoc* ways of rerouting traffic that ease the amount of delay. For a small number of situations, however, large volumes can back up quickly and last for hours, with little, if any, way to mitigate the cumulative total delay. Finding the actual empirical average for these is not simple.

The difference in delay costs between peak and non-peak hours is likely to be especially large for urban freeways. Due to these non-linear effects, delay costs at the average volume on urban freeways are likely to be much smaller than the average delay cost of all crashes, some of which take place during peak hours and impose costs disproportionately higher than the relative traffic volume would indicate. For such non-linear characteristics, it is not sufficient to pick an average traffic volume; the impacts need to be estimated for a range of volumes, and the average weighted by the frequency of each volume. In Table 16, average speed limit, AADT, and the vehicle mix for each roadway type is the median VMT-weighted value for the specified functional classes with the specified number of lanes.

**Table 16. Characteristics of Roadway Types for Modeling**

| Roadway Type | Number of Lanes (Both Directions) | Average Speeds | AADT | Traffic Volume Comprised of Passenger Cars | Traffic Volume Comprised of Single Unit Trucks | Traffic Volume Comprised of Combination Trucks |
|---|---|---|---|---|---|---|
| Urban Interstate/ Expressway | 6 | 60 mi/h | 107,410 | 92% | 3% | 5% |
| Urban Arterial | 4 | 45 mi/h | 27,731 | 95% | 3% | 2% |
| Urban Other | 2 | 35 mi/h | 9,474 | 96% | 3% | 1% |
| Rural Interstate/ Principal Arterial | 4 | 65 mi/h | 25,528 | 80% | 4% | 16% |
| Rural Other | 2 | 55 mi/h | 4,297 | 91% | 5% | 4% |

Standard crash reports usually show the time of the crash, but do not contain information about the hourly volume at the time of the crash. A profile of traffic volume throughout the day allows a volume to be estimated given the time of the crash. This section describes how profiles of diurnal traffic were constructed using data taken from traffic counters on a variety of roadways.

### 3.2.3 Data Sources

The data used to produce the daily volume profiles consist of two pieces, drawn from different data sources. Hourly traffic counts were used to construct average profiles for each road type, and AADT is used to scale the profile.

The traffic counts are drawn from 270 ATR stations across 3 years from 2007 to 2009. The stations used for this analysis are in New York (175) and Massachusetts (95) and represent all of the HPMS functional classifications. Table 17 shows the breakdown of stations by functional class.

The stations collect hourly counts of all vehicles passing by the station, which allows for the construction of an hourly distribution of volume. Normalizing by the daily total, the distribution can be expressed in percent terms and can be scaled using the appropriate AADT taken from the road type daily volume estimates.

**Table 17. Station Counts by Functional Class**

| Functional Class | Station Count |
|---|---:|
| Rural Principal Arterial–Interstate | 17 |
| Rural Principal Arterial–Other | 24 |
| Rural Minor Arterial | 32 |
| Rural Major Collector | 15 |
| Rural Minor Collector | 1 |
| Urban Principal Arterial–Interstate | 61 |
| Urban Principal Arterial–Other Freeways and Expressways | 49 |
| Urban Principal Arterial–Other | 45 |
| Urban Minor Arterial | 22 |
| Urban Collector | 3 |
| Urban Local System | 1 |

### 3.2.4 Data Reduction

The large amount of very specific data is distilled into daily patterns that capture the systematic variation among hours and days while greatly reducing the amount of detailed variation. The relevant time frame for constructing a daily volume distribution is the station-day—one ATR station on one day. One station-day provides 24 hourly volumes and a daily total, for all days of the year. These hourly volumes are then normalized by the daily total to produce a set of 24 percents—representing the percent of daily traffic in that hour. Given a 24-hour percent profile for each station-day, the profiles were then averaged across roadway type group to produce an average profile for each day of the week. These average weekday profiles are then combined and statistically analyzed, producing an analytic expression that closely matches the day-of-week profiles. The result is two functions per roadway type: one that represents weekday travel while the other represents weekend travel.

More formally, the hourly volume is broken into two parts by:

$$\text{volume/hour}_{i,h} = AADT_i \times share_h$$

**Figure 22. Equation. Formula to Determine Volume per Hour**

where $AADT_i$ = average annual daily traffic for roadway type $i$,
$share_h$ = the share or percent of daily traffic falling in hour $h$, of which there are 48 types (24 each for workday and weekend).

This strategy allows the large amount of daily volume data to be boiled down into two prototypical patterns, weekday and weekend, which are adjusted to the daily traffic volume for the road type.

The discussion above outlines the process to construct the daily volume profiles. More detail about the following steps is described below:

- The process for combining the functional classes into a condensed number of roadway type groups.
- The analogous process for collapsing days of the week.
- The criteria used to fit the final analytical functions.

## 3.3 ROADWAY TYPES

The roadway type groups are determined through an iterative process. The above methodology was carried out separately for each functional classification as well as each day of the week. By comparing the resulting functions, it is clear that some of the functional classes can be collapsed because they exhibited the same shape, i.e., the profiles have the same number of similar sized peaks. The absolute and relative heights of the peaks are considered as well as the widths. The tails of the distributions and the early morning and late night hours are also examined. They need to be of similar height and general curvature in order to be aggregated.

The result is five roadway types: Urban Interstate and Expressway, Urban Arterial, Urban Other, Rural Interstate, and Rural Other. For purposes of describing daily volume patterns, Urban Arterial and Urban Other can be summarized with the same mathematical function, but the two are kept separate for delay modeling purposes. The functional classes included in each roadway type are outlined in Table 18.

**Table 18. Roadway Type Components**

| Roadway Type[11] | Included Functional Classes (Functional Class Number) |
|---|---|
| Urban Interstate and Expressway | Urban Principal Arterial—Interstate (11),<br>Urban Principal Arterial—Other Freeways and Expressways (12) |
| Urban Other | Urban Principal Arterial—Other (14),<br>Urban Minor Arterial (16),<br>Urban Collector (17),<br>Urban Local System (19) |
| Rural Interstate | Rural Principal Arterial—Interstate (01) |
| Rural Other | Rural Principal Arterial—Other (02),<br>Rural Minor Arterial (06),<br>Rural Major Collector (07),<br>Rural Minor Collector (08) |

---

[11] Note that the Roadway Types "Urban Arterial" and "Urban Other" have been combined into "Urban Other" due to their mathematical function being identical.

### 3.3.2 Days of the Week

A similar procedure is carried out for days of the week. Initially, a function is produced for each day of the week using the same procedure as outlined above. The same criteria for similar shapes discussed previously are applied to the days of the week. By comparing the resulting functions, the days of the week fall into two groups within a functional class: Monday through Friday appear similar while Saturday and Sunday appear similar. As a result, functions can be collapsed into two groups: weekdays and weekends for each roadway type.

Comparisons were made among different days of the week, different months of the year, and different years. Inevitably there are unusual days and seasons, and volumes as well, but the clearest differences are among functional classes, as above, and weekdays versus weekends.

### 3.3.3 Fitting an Analytical Function

For summarizing daily volume patterns, the criteria for considering a pattern "similar" are guided by balancing the objectives of reducing the amount of detail and preserving relevant variation. Before choosing an appropriate analytical functional form, there are some intermediate steps to help improve the fit of the final functional form. These steps and criteria are outlined below.

The first step is to create weights for each of the points. As noted earlier, the traffic counts are averaged to produce an "average profile" for each roadway type/day combination. The weight assigned to each one of these points is based on the distribution of the counts around that point. Recall that each hourly point in a roadway type/day profile is the mean of the hourly points of the station-days that make up that roadway type/day group. For example, the hourly values of the Urban Interstate Monday profile are the mean of the hourly values of all the station counts on Urban Interstates on Mondays. The weight assigned to this point is the inverse of the variance of those station counts.

The second step is to create a hypothetical zero hour. If the hours of the day are numbered 1 through 24, the zero hour would occur before the hour numbered 1 and is assigned a value and weight equal to that of the 24th hour. Due to the cyclical nature of days—the end of one day leads into the beginning of the next—the left and right tails of the profile should match up in height and slope. The hypothetical value at zero helps ensure that the tails of the profile are aligned. Despite the addition of this zero hour, the relevant range for the volume profile are hours 1–24.

Another step to improve the statistical fit of the data is to assign an alternate weight to the morning peak on weekdays. With the original weight, the function's fit to the data overly smoothed the morning peak for some functional classes. The morning peak is assigned the same weight as the afternoon peak.

As noted above, there are ultimately two profiles for each roadway type: weekdays and weekends. The final weekday curves are fit to 125 points (24 hours, plus a zero hour, for 5 days of the week) while the weekend curves are fit for 50 points (24 hours, plus a zero hour, for Saturday and Sunday). Thus, each hour had five points associated with it for weekdays and two for weekends; each point is given a weight as described above.

The criteria for selecting a final analytical curve are as follows: smoothness, number of peaks, curvature in the tails, and absence of singularities. The smoothness criterion is simply how smooth the function was. The desired function should transition smoothly between hours and should be overall "well behaved" with no discontinuities or edges. The number of peaks criterion is to ensure the function fit to the data. For weekday data, there are two clear peaks exhibited. Weekend data exhibit one clear peak. The curvature in the tails, as described above is intended to help describe the cyclical nature of the distributions. The general criterion is that the curvature and height on the left tail approximate the curvature and height on the right hand tail. Lastly, the chosen analytical function could not have any singularities in the relevant range: in this case, zero to 24. However, singularities outside of that region may also influence the curvature of the function in the tails; especially if that singularity is near the relevant interval.

Figure 23 and Figure 24 show the resulting parameterized curves for each of the four roadway type groups for weekdays and weekends respectively. Note the general smoothness of the function as well as the bi-modal shape of the weekday function. The weekend graph shows the curvature in the tails being similar on the right and the left. The estimated equations for each of the four roadway type groups are listed in Table 19.

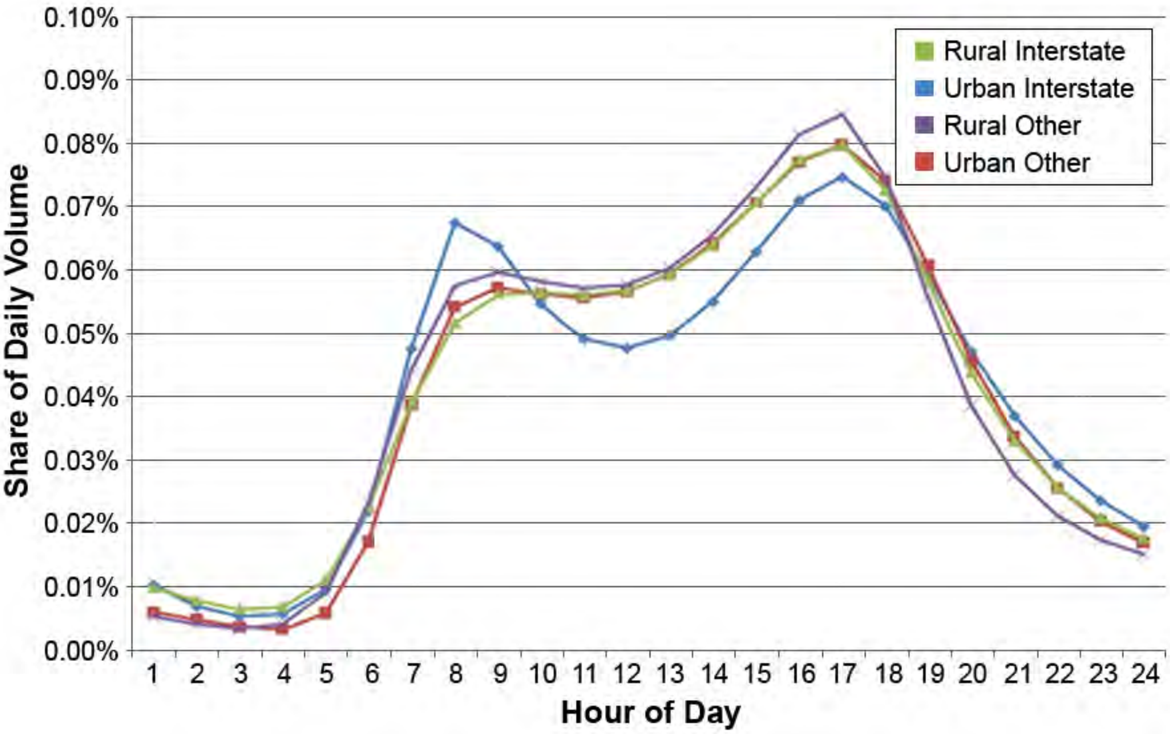


Figure 23. Percent Daily Volume—Weekdays

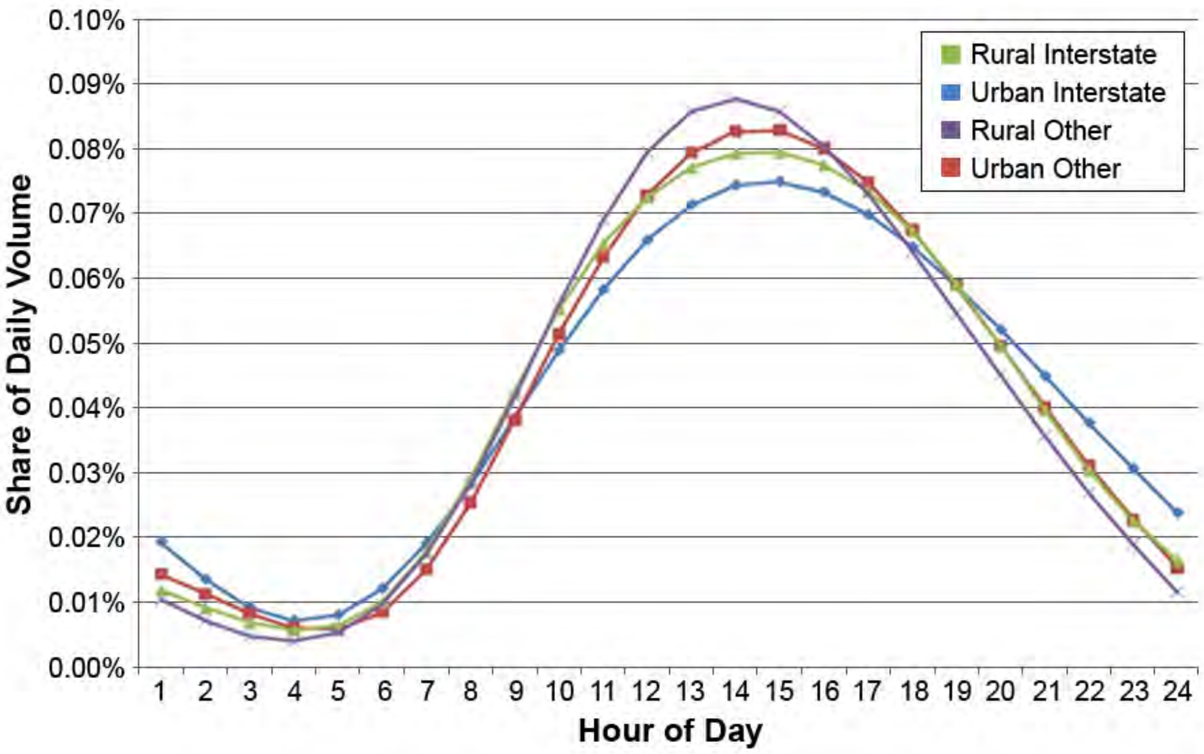
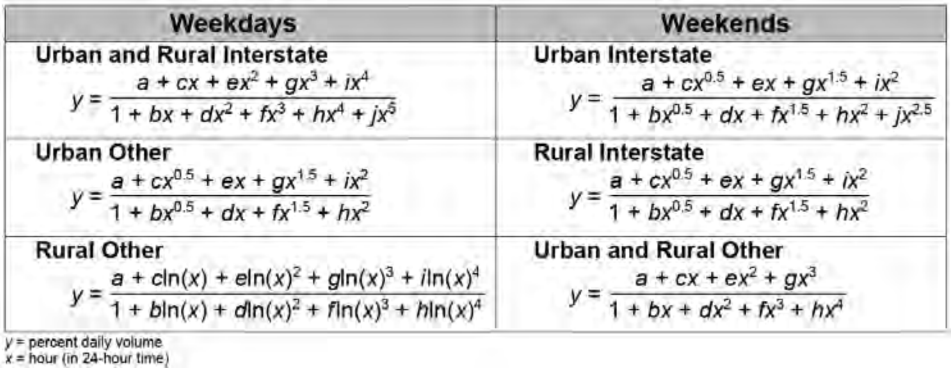


Figure 24. Percent Daily Volume—Weekends

### 3.3.4 Scaling the Volume Profiles

For a given crash on a given roadway type at a given time of day and day of the week, the above results allow the share of daily volume to be extracted for that crash. Given its roadway type profile, an appropriate AADT can be applied to convert the share to an absolute volume, using the equation shown in Figure 22. By multiplying the distribution by an AADT value, the profile then represents the estimated volume at each hour, rather than the estimated fraction of daily volume. The VMT-weighted median AADT for each functional class (with the specified number of lanes) from HPMS is listed in Table 16.

Figure 25 displays the equations for the various highway types on weekdays and weekends for traffic flow rates. Table 19 defines the coefficients that appear in the equations.



| Weekdays | Weekends |
|---|---|
| **Urban and Rural Interstate**<br>$y = \frac{a + cx + ex^2 + gx^3 + ix^4}{1 + bx + dx^2 + fx^3 + hx^4 + jx^5}$ | **Urban Interstate**<br>$y = \frac{a + cx^{0.5} + ex + gx^{1.5} + ix^2}{1 + bx^{0.5} + dx + fx^{1.5} + hx^2 + jx^{2.5}}$ |
| **Urban Other**<br>$y = \frac{a + cx^{0.5} + ex + gx^{1.5} + ix^2}{1 + bx^{0.5} + dx + fx^{1.5} + hx^2}$ | **Rural Interstate**<br>$y = \frac{a + cx^{0.5} + ex + gx^{1.5} + ix^2}{1 + bx^{0.5} + dx + fx^{1.5} + hx^2}$ |
| **Rural Other**<br>$y = \frac{a + c\ln(x) + e\ln(x)^2 + g\ln(x)^3 + i\ln(x)^4}{1 + b\ln(x) + d\ln(x)^2 + f\ln(x)^3 + h\ln(x)^4}$ | **Urban and Rural Other**<br>$y = \frac{a + cx + ex^2 + gx^3}{1 + bx + dx^2 + fx^3 + hx^4}$ |

$y$ = percent daily volume
$x$ = hour (in 24-hour time)

Figure 25. Equations. Formulas to Determine Traffic Flow Rates

**Table 19. Daily Volume Parameters**

| Weekdays | | | | |
|---|---|---|---|---|
| **Coefficient** | **Urban Interstate** | **Urban Other** | **Rural Interstate** | **Rural Other** |
| a | 0.01764112400 | 0.00758558200 | 0.01217750800 | 0.00530943700 |
| b | 0.14796594400 | -1.20286400000 | -0.28449172000 | -1.67743583000 |
| c | -0.00841684000 | -0.01015332000 | -0.00591094000 | -0.01030073000 |
| d | -0.13735799000 | 0.53711786400 | 0.02146555900 | 1.05188298900 |
| e | 0.00154920000 | 0.00491378500 | 0.00105492700 | 0.00741814600 |
| f | 0.02190901600 | -0.10512603000 | 0.00096698200 | -0.29121999000 |
| g | -0.00010561000 | -0.00100632000 | -0.00006592200 | -0.00229244000 |
| h | -0.00132138000 | 0.00761396000 | -0.00015873000 | 0.02999625000 |
| i | 0.00000296791 | 0.00007454960 | 0.00000144444 | 0.00025651500 |
| j | 0.00002788320 | | 0.00000444131 | |
| **Weekends** | | | | |
| **Coefficient** | **Urban Interstate** | **Urban Other** | **Rural Interstate** | **Rural Other** |
| a | 0.02439630100 | 0.01718422300 | 0.01649975400 | 0.01436327600 |
| b | 198.74573320000 | -0.24050789000 | -1.04796983000 | -0.17032005000 |
| c | 5.42238114800 | -0.00666137000 | -0.02049013000 | -0.00633232000 |
| d | -186.43026500000 | 0.02644769800 | 0.41714382100 | 0.01448492900 |
| e | -5.86023019000 | 0.00083263300 | 0.00921674700 | 0.00092584100 |
| f | 72.12835487000 | -0.00129011000 | -0.07398814000 | -0.00059093000 |
| g | 2.04428319700 | -0.00002275400 | -0.00173934000 | -0.00002714900 |
| h | -13.13006680000 | 0.00002660410 | 0.00492762300 | 0.00001404200 |
| i | -0.21336114000 | | 0.00011711500 | |
| j | 0.96558776600 | | | |

### 3.3.5 Weekday and Weekend Volumes

Because the daily profiles are estimated separately for weekdays and weekends, a separate volume for each needs to be developed. HPMS AADTs do not differentiate between weekends and weekdays. The ATR data, however, can be analyzed separately for weekends and weekdays. An average daily total was calculated for all the ATR stations for weekends, weekdays, and the entire sample. The ratio between the weekend mean and the total and the weekday mean and the total provide scaling factors to transform the single AADT number provided in HPMS into a weekday and weekend number. The results are shown in Table 20.[12]

---

[12] The Urban Other roadway type group curve is applied to the volumes for both Urban Principal Arterial and Urban Other roadway types.

Table 20. Weekend and Weekday AADT

| Road Type | Weekend/Weekday | AADT Factor | Factored AADT |
|---|---|---|---|
| Urban Interstate/Expressways | Weekend | 0.86 | 92,210 |
| Urban Interstate/Expressways | Weekday | 1.06 | 113,562 |
| Urban Principal Arterial | Weekend | 0.86 | 23,807 |
| Urban Principal Arterial | Weekday | 1.06 | 29,320 |
| Urban Other | Weekend | 0.86 | 8,133 |
| Urban Other | Weekday | 1.06 | 10,016 |
| Rural Interstate & Principal Arterials | Weekend | 0.94 | 23,929 |
| Rural Interstate & Principal Arterials | Weekday | 1.03 | 26,172 |
| Rural Other | Weekend | 0.94 | 4,028 |
| Rural Other | Weekday | 1.03 | 4,405 |

### 3.3.6 Probability of Crash Duration

An important factor affecting the cost of an individual crash is how long the roadway is closed as a result of the crash. The term “duration” describes the length of time the road is closed due to the crash, as opposed to “incident duration” which describes the length of time before the traffic backup is dissipated and traffic resumes moving normally.

While no nationwide source of data on duration of road closure was found, three State-level crash databases were obtained after contacting the Departments of Transportation (DOTs) and highway patrol administrations of the 50 States. The Kentucky State Police Criminal Identification and Records Branch provided comprehensive information on 10,893 CMV crashes from 2006 to 2008. The Pennsylvania Department of Transportation (PennDOT) Bureau of Highway Safety and Traffic Engineering provided data on 23,388 CMV crashes during 2006 through 2008. Finally, Washington State Patrol, Field Operations Bureau HQ and Washington State Department of Transportation (WSDOT) Traffic Operations provided data on 4,311 CMV crashes during the same period. Washington State data were not used in this study; although the data appeared to be precise, it only covered a limited number of the interstates and arterials, reducing the applicability of the data to a wider range of circumstances.

The data from PennDOT provides a description of truck type, the severity of the crash (three levels), some information on location of the crash,[13] and the duration of the road closure resulting from the crash, split into categories of time and an indication of whether the road was partially or fully closed. The Kentucky data provides information on truck type, crash severity, location of the crash,[14] and duration information expressed as the number of minutes of road closure (a continuous variable). Table 21 presents a summary of the data available from each State.

---

[13] The Pennsylvania location information includes the street name and in some cases latitude and longitude coordinates of the crash.

[14] The Kentucky location information is roadway name and milepost.

**Table 21. State-Level Crash Data Relating to Duration of Road Closure**

| Data Element | Pennsylvania | Kentucky | Washington |
|---|---|---|---|
| Truck Type | Yes | Yes | No |
| Severity | 3 levels | 3 levels | No |
| Functional Class | Identified for a subset of crashes via geocoding | Identified for a subset of crashes via geocoding | Only Principal Arterials |
| Duration | Categories, partial and full | Continuous | Continuous, only for durations greater than 90 minutes |
| Time of Day | No | No | Yes |
| Number of Crash Records | 23,388 | 10,893 | 4,311 |

A subset of the truck crash location data from Pennsylvania and Kentucky was able to be geocoded and located on the roadway network. Once located, the HPMS functional classification was determined. These crashes are most likely to be on larger roadways and this may bias the sample of all crash locations.

Analysis of the data shows that crash severity is the strongest indicator of the duration of road closure after a CMV crash. Truck type and functional class of the roadway are also expected to affect duration of a road closure, but the data from a single State is too sparse to allow for more granular detail. That is, duration of closure that is specific to severity and truck type and/or functional class cannot be calculated with much confidence because occurrences of each combination of truck type and severity for a certain State are too rare to build a robust estimate of road closure duration. The analysis uses the duration categories from the Pennsylvania data which are presented in Table 22 and Table 23.

The probabilities across each type of closure sum to 100 percent (or close to 100 percent depending on rounding) for each severity type. The categories of road closure are somewhat wide in some cases.

The data from Kentucky, because it contained a continuous representation of duration of road closure, was queried to determine what the median length of duration was for a given duration category. The median points are displayed in the headings of Table 22 and Table 23.

**Table 22. Probability of No Closure and Partial Closures by Severity**

| | No Closure | 0–30 min | 30–60 min | 1–3 hrs | 3–6 hrs | 6–9 hrs | >9 hrs |
|---|---:|---:|---:|---:|---:|---:|---:|
| **Median Duration** | | **15 min** | **45 min** | **90 min** | **4 hrs** | **7 hrs** | **9 hrs** |
| PDO | 50% | 11% | 11% | 5% | 1% | 0% | 0% |
| Injury Only | 38% | 10% | 12% | 5% | 1% | 0% | 0% |
| Fatal | 7% | 0% | 2% | 6% | 4% | 1% | 1% |
| **All Severity** | **47%** | **11%** | **11%** | **5%** | **1%** | **0%** | **0%** |

**Table 23. Probability of Full Closure by Severity**

|  | 0–30 min | 30–60 min | 1–3 hrs | 3–6 hrs | 6–9 hrs | >9 hrs |
|---|---|---|---|---|---|---|
| **Median Duration** | **15 min** | **45 min** | **90 min** | **4 hrs** | **7 hrs** | **9 hrs** |
| PDO | 4% | 7% | 7% | 3% | 1% | 0% |
| Injury Only | 5% | 11% | 11% | 4% | 1% | 1% |
| Fatal | 1% | 2% | 24% | 32% | 12% | 7% |
| **All Severity** | **4%** | **7%** | **8%** | **3%** | **1%** | **1%** |

## 3.4 VEHICLE DELAY

### 3.4.1 Data Groundwork

The previous sections of this section have described the data needed to lay the foundation for modeling the traffic movements around a road closure due to a crash. The data are used to specify the roadway conditions of the prototypical crashes: roadway configuration (number of lanes), volumes, and duration of road closure. These descriptors are then supplied to other models to derive the roadway-type-specific functions that translate duration of road closure and traffic volume into an estimate of expected total vehicle delay hours.

Running the vehicle delay models for every possible combination of factors was cost prohibitive. Separately modeling each unique combination of the 5 roadway types, 13 closure duration categories, and 48 traffic volumes specific to each hour of the day for weekdays and weekends would produce more than 3,000 scenarios. Instead, the microsimulation delay model is used to generate estimates for a select number of combinations of duration of road closure and volumes. The resulting estimates are then used as data points to estimate a roadway-type-specific function relating volume and duration to total vehicle delay.

The remainder of this section discusses the specifics of how the vehicle delay is modeled, given the descriptors of the crash scenario of interest and discusses the interpolation and extrapolation necessary to estimate a generalizable function relating volume and duration to vehicle delay hours.

### 3.4.2 Components of Delay

Delay can be divided into two components partially aligned with the phases of an incident:

- Backup delay on the roadway where the crash occurs, consisting of detection, clearance, and dissipation of the traffic backups.
- Impacts of diverted traffic on the rest of the network.

### 3.4.3 Backup Delay

The time between when a crash occurs and when emergency services arrive on the scene to begin treatment is a period when nothing is being done to mitigate the impacts other than what participants and bystanders can do. Urban expressways are well-instrumented with detectors and cameras, so knowledge of the occurrence is almost instantaneous. Cellular telephone users start calling in almost immediately. Congestion, however, may slow down the arrival of emergency services. At peak times on urban expressways and arterials, traffic backups build up rapidly, and vehicles are stopped with engines idling.

Accidents in rural areas may take somewhat longer to detect, and emergency equipment typically needs to travel farther, but can readily gain access.

Tow trucks remove disabled vehicles and ambulances carry off injured persons, and then police investigate the circumstances of the crash. In severe (not necessarily fatal) expressway crashes, the number of vehicles and injuries may be 50 to 100, each requiring a separate emergency vehicle. In most cases, traffic does not move during this phase.

Partial closure from a crash incident is also modeled. The time required to dissipate the backup that has built up behind the crash depends upon the size of the backup, the amount of capacity that is restored, and the continuing arrival rate. These assumptions are listed in Table 26 and in Table 27.

### 3.4.4 Network Delay

For a severe crash that will take time to clear, police will shut off entrances to the highway. People intending to use the section of road then must find another way to reach their destinations. Some drivers may divert before an incident if there is an exit available within view of the congestion. After some length of duration, no additional vehicles enter the backup behind the blockage, but congestion on the rest of the network is increased due to the additional load. Opportunities for diversion reduce the cost of the delay upstream of the crash, but spread at least some of that delay and emissions to other parts of the network.

Network delay depends heavily on a host of factors, some pertaining to the density of the network and alternative routes, some affected by police actions that close or divert traffic. Variable message signs (VMS) and other traffic information sources may reduce the backup and increase diversion. Even the difference between typical urban versus rural conditions is hard to generalize. Modeling them is arduous and not necessarily representative.

The correct estimate for the incremental network delay from an additional vehicle is the marginal cost rather than the average cost, i.e., the additional delay to all vehicles rather than just those diverted.

### 3.4.5 Vehicle Delay Estimation Methods

A deterministic queuing model can represent the major cost impact, namely, delay. In the backup model shown in Figure 26, the slope of the main diagonal line shows the arrival rate for traffic on the highway. After the incident is cleared, traffic is assumed here to flow at capacity until the backup is dissipated.

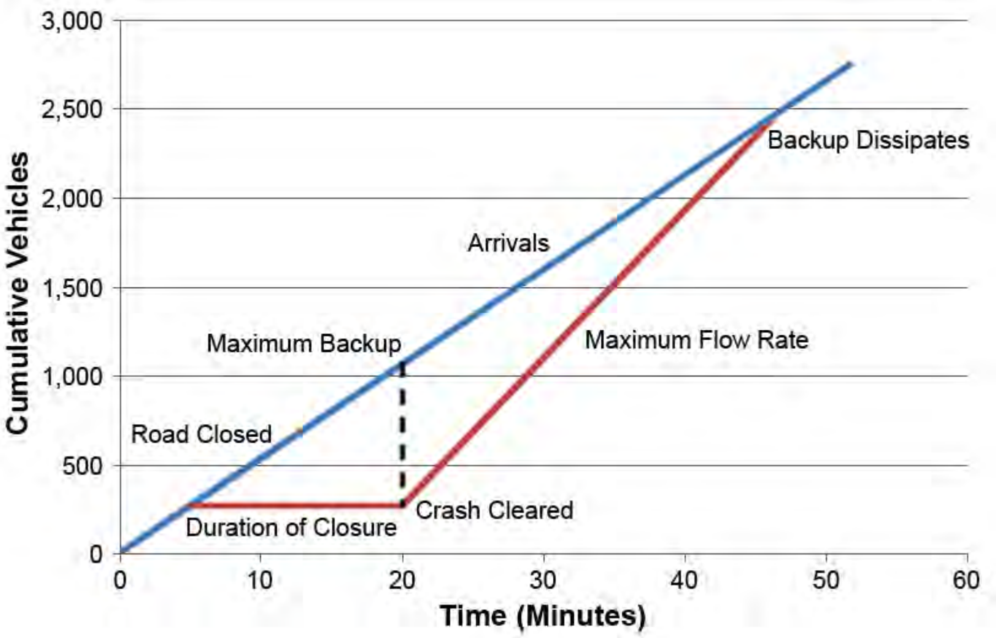


**Figure 26. Deterministic Queuing Model**

For some subset of conditions, microscale simulations are constructed to verify the deterministic models and determine if they are biased for any given set of parameters. An advantage of a simulation is that it can produce many of the delay and emissions costs from the same set of model runs (multiple runs are required for each set of parameters in order to derive central tendencies for randomized Monte Carlo impacts).

### 3.4.6 Traffic Simulation

Traffic modeling simulation tools provide the ability to create post-crash scenarios on hypothetical roadways and measure vehicle behavior. Multiple runs can be generated and since the inputs are adjusted by stochastic (random) values the outputs create a distribution of results. The rates of vehicle arrival intervals, diversion, driver aggression level, lane changing, vehicle type, emergency response actions, rubbernecking, dynamic lane closure(s), and lane capacity variations can all be adjusted via a software-based simulation model. A graphical user interface also provides the opportunity to assess if realistic vehicle interactions are simulated with the selected inputs.

For purposes of crash cost estimation, a microsimulation tool serves three functions:

- Simulation tool results can validate deterministic calculation methods.
- A simulation tool offers a proxy method for obtaining field data without the sizable hurdles associated with actual onsite collection.
- The software provides comprehensive precise location and vehicle performance data that can be used for emission modeling.

Simulated road sections attempt to model an “average” road for that roadway type (i.e., number of lanes, lane width, distance between exits, grade, etc.) for a range of volumes and incident durations.

### 3.4.7 Selected Scenarios

As mentioned previously, it is cost prohibitive to run the model on the more than 3,000 scenarios that would explore the entire range of relevant characteristics for crashes. Therefore, the vehicle delay models are run on just a subset of the possible scenarios.

### 3.4.8 Volumes Used in Delay Simulations

The choice of which volumes to use for the selected simulations is informed by the daily curve research described above. The final volumes selected are presented in Figure 27 and Figure 28.

Figure 27 presents the scaled daily distributions for each of the roadway types. Figure 28 presents the same information, but sorted to display the range of values in each distribution. The black lines indicate simulation volumes selected for those roadway types. The volumes were selected to provide a reasonable range for simulation so that any future interpolation would be on the interior of the simulated points, rather than the alternative of extrapolating to higher volumes. A similar approach (of choosing a range of volumes) was also used for the smaller functional classes. Each of the five roadway types has at least two volumes selected for analysis. The Urban Interstate/Expressways had three volumes chosen because there was such a large fluctuation of volume throughout the day. There is also an implied delay of zero vehicle hours if the crash were to occur when there was no other traffic on the roadway. The exact volume values chosen are shown in Table 24.

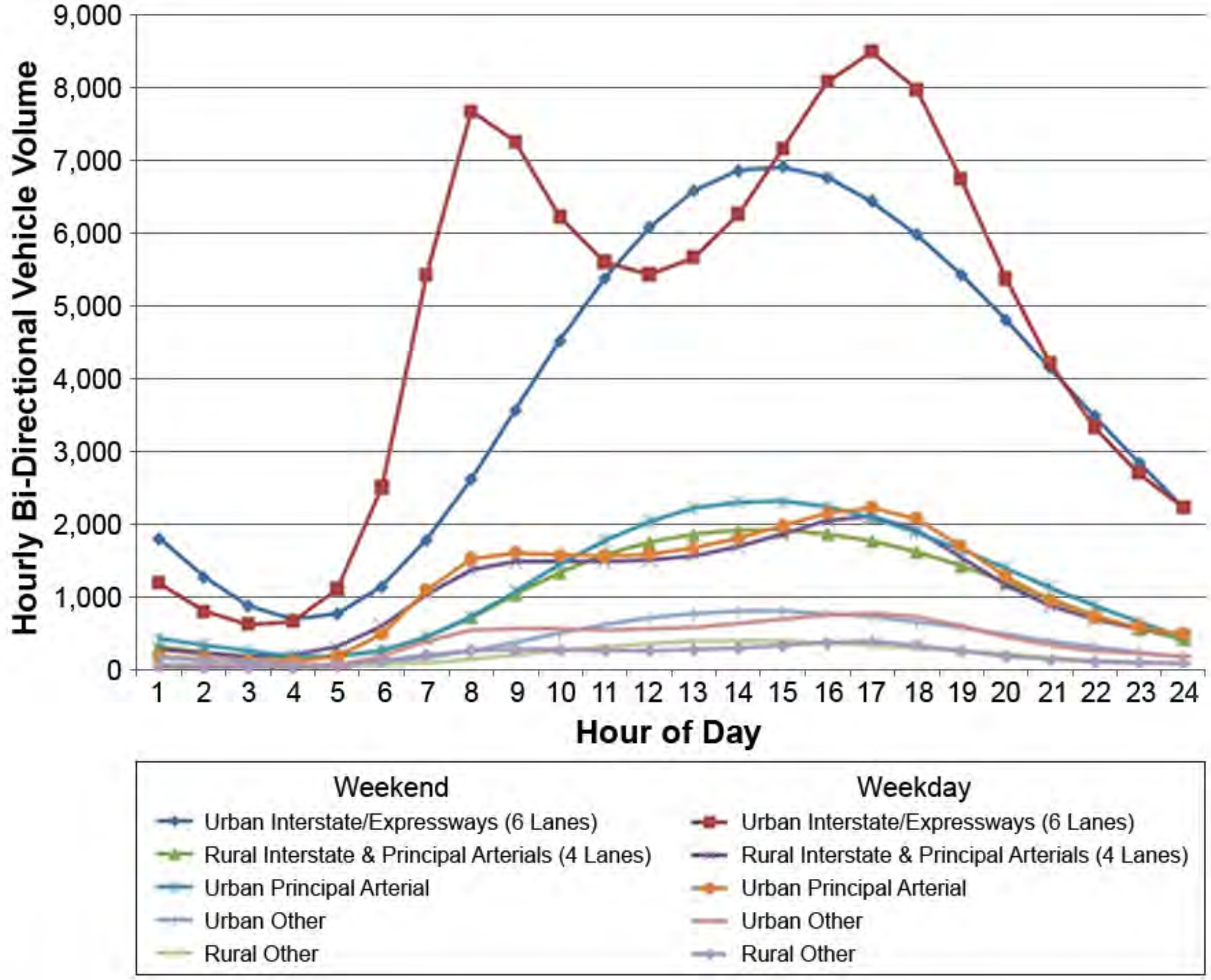


**Figure 27. Daily Volumes by Roadway Type**

### 3.4.9 Durations for Simulations

As shown in Table 22 and Table 23, the data available to ascribe different road closure durations to different crash severities has 13 different categories of road closure duration. Simulations are run on just a subset of the possible duration categories available to save computing resources. Each roadway type and volume scenario was run on seven road closure durations:

- No closure (rubbernecking is the only source of delay).
- Full closures of 15 minutes, 90 minutes, and 4 hours.
- Partial closures of 15 minutes, 90 minutes, and 4 hours.

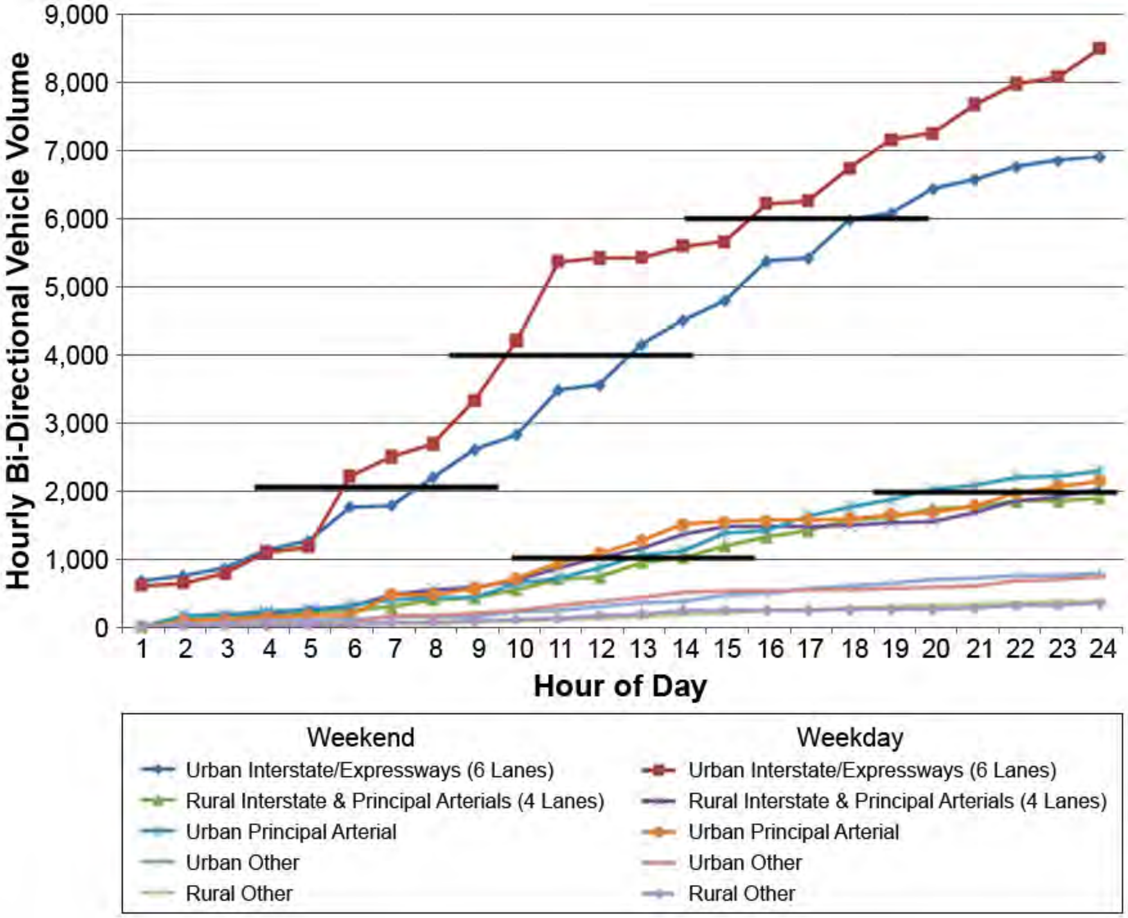


**Figure 28. Daily Volumes (Sorted) and Simulated Volumes**

The thick horizontal black lines in Figure 28 represent the volumes that were chosen to simulate relative to the overall distribution of volumes. For example, the red and blue lines represent hourly volumes on six-lane urban interstates (sorted into ascending order). The volumes that were chosen to simulate low, medium, and high volumes are the black lines at 2,000, 4,000, and 6,000 vehicles per hour (bi-directional volume).

**Table 24. Hourly Volumes for Simulations**

| Roadway Type | Hourly Volumes for Simulations (Both Directions) |
|---|---|
| Urban Interstate/Expressway | 6,000, 4,000, 2,000 |
| Urban Arterial | 2,000, 1,000 |
| Urban Other | 600, 300 |
| Rural Interstate/Principal Arterial | 2,000, 1,000 |
| Rural Other | 300, 100 |

### 3.4.11 Diversions

For full closures of longer durations, the analysis simulates road closure. It is assumed that for very severe crashes (long duration road closures) either the police would close the roadway and direct new traffic to detours, or motorists themselves would learn about the obstruction and find their own detours. Specifically, after 45 minutes for the 90-minute duration run and after 1 hour for the 4-hour duration run, no new traffic is introduced to the traffic simulation tool. These diversion rates were based on the assumption that highway patrol and local police require a period of assessment and consultation before they can establish a detour. No actual field data capturing truck crash road diversion implementation times were readily available. The delay from the diverted traffic is estimated as a separate deterministic calculation covered in the previous section.

### 3.4.12 Partial Reopening

Crashes that initially result in full road closures are likely to open up in stages. Informal consultations with highway patrol personnel confirmed that one of the goals of responders after tending to victims is to get at least some traffic moving. Traffic can therefore move while the crash is further cleared and the roadway is completely reopened. To account for the phased nature of crash clearance, the roadway is opened up one increment halfway through the road closure incident. Specifics of the partial reopening for each scenario are given in the following sections.

### 3.4.13 Traffic Simulation Package

The traffic simulation was performed via the traffic microsimulation tool, TSIS-CORSIM. This software was developed by the University of Florida McTRANS Center and is supported through FHWA funding.[15] The software produces many outputs including aggregate vehicle delay hours and fuel consumption. It also produces second-by-second vehicle performance, and these binary code vehicle trajectory outputs can be used for increased accuracy for emissions modeling (the subject of Section 4). This novel method to obtain more accurate vehicle emissions was suggested by John Byun at the 2007 Transportation Research Board Annual Forum (Byun, 2007).

An important step in this project was developing a software program to translate the vehicle performance data (precise acceleration and deceleration data) into vehicle specific power (VSP). VSP is a proxy variable for engine load that has been shown to be highly correlated with emissions and produces more accurate emissions estimates than simply assuming constant velocities (Zhai, Frey, & Rouphail, 2008). The emissions methodology is covered in the following sections.

A representation of each of the five roadway types used for the cost model is needed to perform the traffic simulations. Roadway networks were constructed via the TRAFED (TSIS Traffic Network Editor) graphic user interface (GUI). Within the GUI, the expressway link tool (FRESIM) and the surface link tool (NETSIM) are combined enabling designers to build a connected network. The networks were translated into functional code and then run via the CORSIM simulation feature.

---

[15] McTrans Center (2010).

Descriptions of each of the five roadway configurations are provided below. However, a number of the simulation parameters are uniform across all five modeled road configurations. Driver aggression distributions are specified by TSIS-CORSIM default settings. Vehicle performance specifications and headway distances are also kept at default settings. Road gradient is assumed to be zero degrees (flat) for all roads and lane width is always 12 feet. The length of the road segments modeled is sufficient to accommodate the maximum backup length to capture impacted traffic.

Lane vehicle capacity is reduced in open lanes adjacent to closed lanes because of drivers' curiosity and desire to visually assess the incident. This phenomenon is referred to as “rubbernecking” and TSIS-CORSIM contains a feature to adjust capacity of each lane with a rubbernecking factor to simulate this source of capacity loss. The rubbernecking factors used in this analysis are from recent field data (Chin, Franzese, Greene, & Hwang, November 2004). See Table 25 for the rubbernecking factors adopted for the simulation runs. Roadway links without a crash or specified rubbernecking segments use TSIS-CORSIM default values for roadway design vehicle capacity based on the 2000 Highway Capacity Manual (Transportation Research Board, 2000).

**Table 25. Factors for Capacity Reduction Due to Freeway Crashes (Normal Capacity = 1.000)**

| Effect of Crash | 1 Freeway Lane | 2 Freeway Lane | 3 Freeway Lane | 4 Freeway Lane | 5+ Freeway Lane |
|---|---:|---:|---:|---:|---:|
| Vehicle on Shoulder | 0.45* | 0.75 | 0.84 | 0.89 | 0.93† |
| 1 Lane Blocked | 0.00 | 0.32 | 0.53 | 0.56 | 0.75 |
| 2 Lanes Blocked | N/A | 0.00 | 0.22 | 0.34 | 0.50 |
| 3 Lanes Blocked | N/A | N/A | 0 | 0.15* | 0.20* |
| 4 Lanes Blocked | N/A | N/A | N/A | 0 | 0.10* |

* Represents assumed values

† Source: Chin, Franzese, Greene, & Hwang, November 2004

Multiple stochastic Monte Carlo runs were conducted for each simulation. TSIS-CORSIM developers recommended conducting 10 runs to establish baseline condition scenarios (without crashes) and 40 runs for the crash scenarios. The parameters that vary in the stochastic runs are the distribution of free-flow speed by driver type (aggression level), car-following sensitivity factor, lane change acceptance parameters, timing of vehicle entries onto the roadway within each hour, and parameters affecting the number of and timing related to discretionary lane changes.

Each of the five facility designs are tailored using the available TSIS-CORSIM incident simulation features to approximate post-crash conditions. Some of the simulations require additional adaptation to simulate certain crash scenarios. The following narrative provides detailed descriptions of the various road configurations and the associated scenarios.

### 3.4.14 Urban Interstate/Expressway

The constructed roadway is a single freeway span with three lanes in each direction of travel with free-flow speed of 65 mi/h. The traffic is comprised of 3 percent single unit trucks, 5 percent double unit trucks and the rest passenger cars. The total length of the roadway is 10 miles; the roadway is comprised of three links in each direction. The crash site is located 8 miles downstream of the entry node. The simulated road consists of only bi-directional expressway segments, with entry and exit nodes at the ends of the road. See Figure 29, for a screenshot of the simulated expressway. Vehicle coloration corresponds to randomly assigned aggression levels. Cars, single unit trucks, and double unit trucks are present on the roadway. The red section indicates the crash site on the eastbound side and the adjacent downstream road portion that is closed, while the yellow section marks the 300-foot approach buffer to the crash site. The buffer is used to account for anticipatory braking effect.

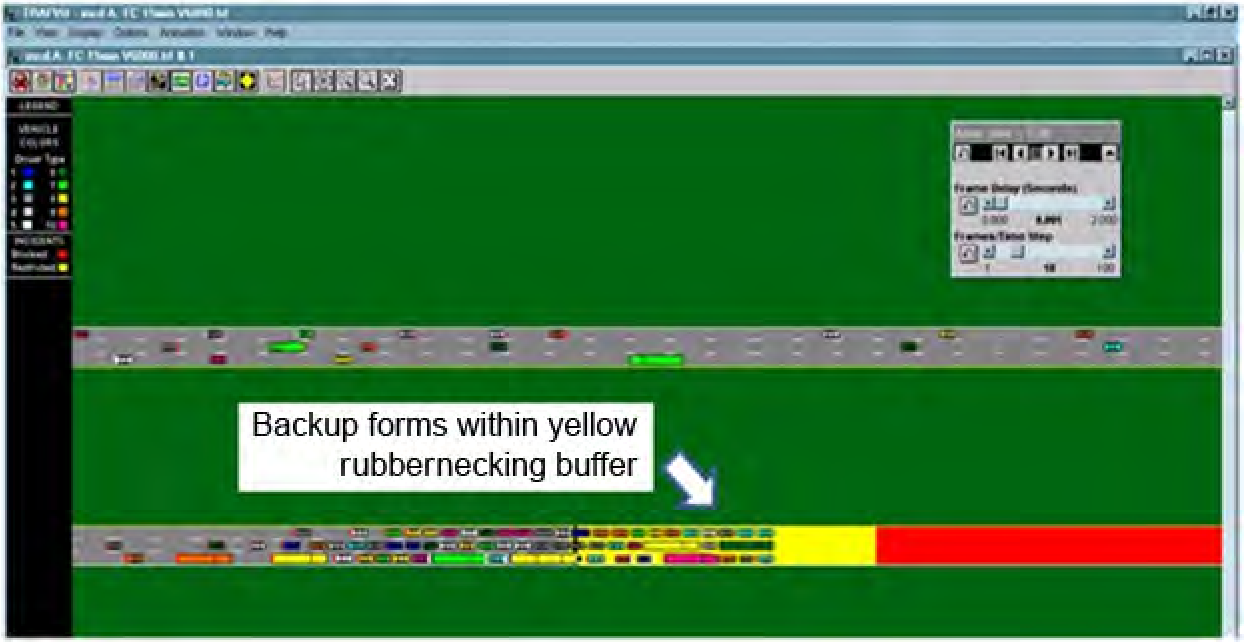


Figure 29. Urban Interstate/Expressway

The westbound traffic rubbernecking distance also contains an “incident zone” of 500 feet, with reduced capacity to account for driver curiosity, viewing the truck crash side of the roadway. The rubbernecking capacity reduction starts 5 seconds after the crash blockage occurs. Rubbernecking factors for the non-crash side of the expressway are constant for all time periods and all types of lane closure (partial and full).

Lane closures are modeled as either partial or full road closures. For partial closures the 15 minute duration blocks the middle and right lane for the full time. The 90- and 240-minute partial closure scenarios block the same two lanes for half of the lane closure duration, and then shifts to a single lane closure after half the lane closure time has elapsed. Initially, full closure scenarios block all three eastbound lanes. For the 15-minute scenario these lanes remain closed for the entire duration; for the 90-minute scenario one lane opens after 45 minutes while the remaining lane opens after 90 minutes. For the 240-minute scenarios, additional traffic is diverted after 60 minutes; the blocked traffic is allowed to pass through the crash site using one lane with a high rubbernecking factor 2 hours into the crash scenario. The entire roadway is cleared after the entire 240-minute duration has elapsed. A summary of diversion rules for all roadway types can be found in Table 26.

### 3.4.15 Urban Arterial

The roadway simulation for an Urban Arterial crash includes a basic network consisting of the four-lane arterial (two lanes in each direction) containing the crash site, connected secondary roads, and a central expressway. Free-flow speed of the arterial is 45 mi/h with the vehicle mix shown in

Table 16. The traffic is comprised of 3 percent single unit trucks, 2 percent double-unit trucks, and the rest passenger cars. The intersections between the arterial and secondary roads (spaced 1 mile apart) force acceleration and deceleration behavior on the traffic. Recall that tracking the drive cycle of the traffic is an important advance of this analysis. NETSIM does not have roadway capacity adjustment features, so no rubbernecking factors were included in this or any of the other non-expressway scenarios.

Figure 30 displays the Urban Arterial network. The Urban Arterial is the vertical road section in the middle, there is an expressway running in the center of the network running horizontally (gray lines); and exit and entry ramps for the expressway. Additionally, there is a secondary set of roads that connect the Urban Arterial to the expressway and these have free-flow speeds of 30 mi/h, which is the TSIS-CORSIM default for urban surface roads. The free-flow speed for the expressway is 60 mi/h. The Urban Arterial has two lanes of travel in each direction as does the expressway. Secondary roads have a single lane of travel for each direction.

Traffic signals are calibrated to enable full traffic backup dissipation for at least 95 percent of the light signal cycles under baseline (non-crash) conditions. Partial closures are easily simulated using a NETSIM incident tool that allows for temporary blockage for a single lane. To simulate partial closures one of the two lanes is blocked for the specified duration. The maximum blockage time for the NETSIM tool is 167 minutes, therefore the 240-minute partial closure delay estimates are extrapolated from the shorter duration runs. Full closure simulations require a novel usage of an inserted “dummy” node with adapted traffic signal features to hold the traffic for certain time periods.

The diversion rules for Urban Arterials differ from those for Urban Expressways. For the 90-minute scenario, a maximum backup length of 1 mile was enforced. Traffic beyond that length diverted. The roadway was opened fully after the 90-minute duration had elapsed. For the 240-minute duration, the same maximum backup length was enforced, but the roadway was partially opened after 60 minutes. The remaining lane was opened after the entire duration elapsed. Differing from the expressway scenarios, the secondary roads permitted additional traffic volume to enter the network throughout the full closure scenarios. The additional vehicles originated at expressway entry links and 10 percent of traffic volume exited the freeway onto the surface roadways. See intersection nodes and expressway ramps in Figure 30.

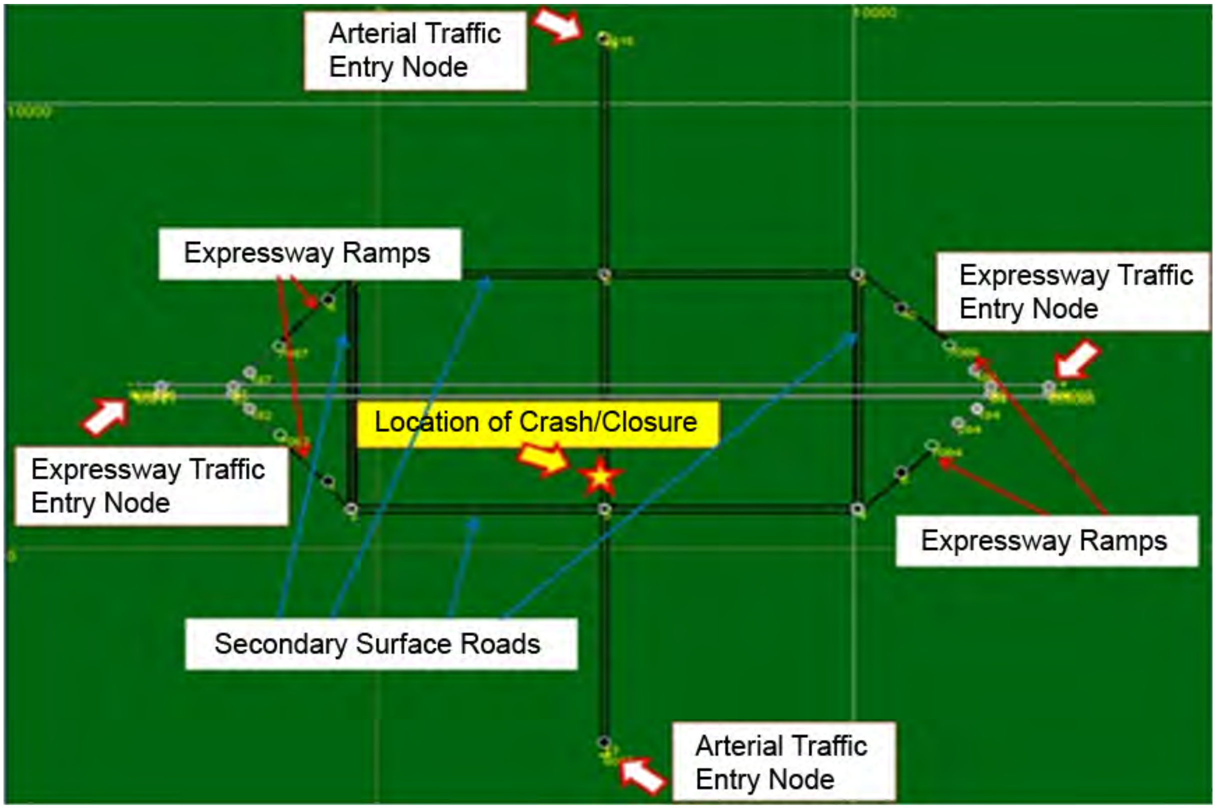


**Figure 30. Urban Arterial**

### 3.4.16 Urban Other

For Urban Other roadways (Minor Arterials, Collectors, and Local roads) a simplified network similar to the Urban Arterial is created through TRAFED. The link length for the targeted Urban Other road is 0.25 miles to represent the distance between Urban Minor Arterials (e.g., avenues in grid cities). All Urban Other links have single lanes for each direction of travel. The free-flow speed is 30 mi/h, and the percent truck mix is 3 percent for single unit and 1 percent for double unit based on HPMS data. There are no traffic signals on Urban Other intersections. Figure 31 displays the Urban Other simulated network.

Similar to the Urban Arterial scenario, the Urban Other network includes an expressway and connecting secondary surface roads. The connected roads have the same default speed settings for the Urban Arterial scenario (expressways at 65 mi/h; surface roads at 30 mi/h).

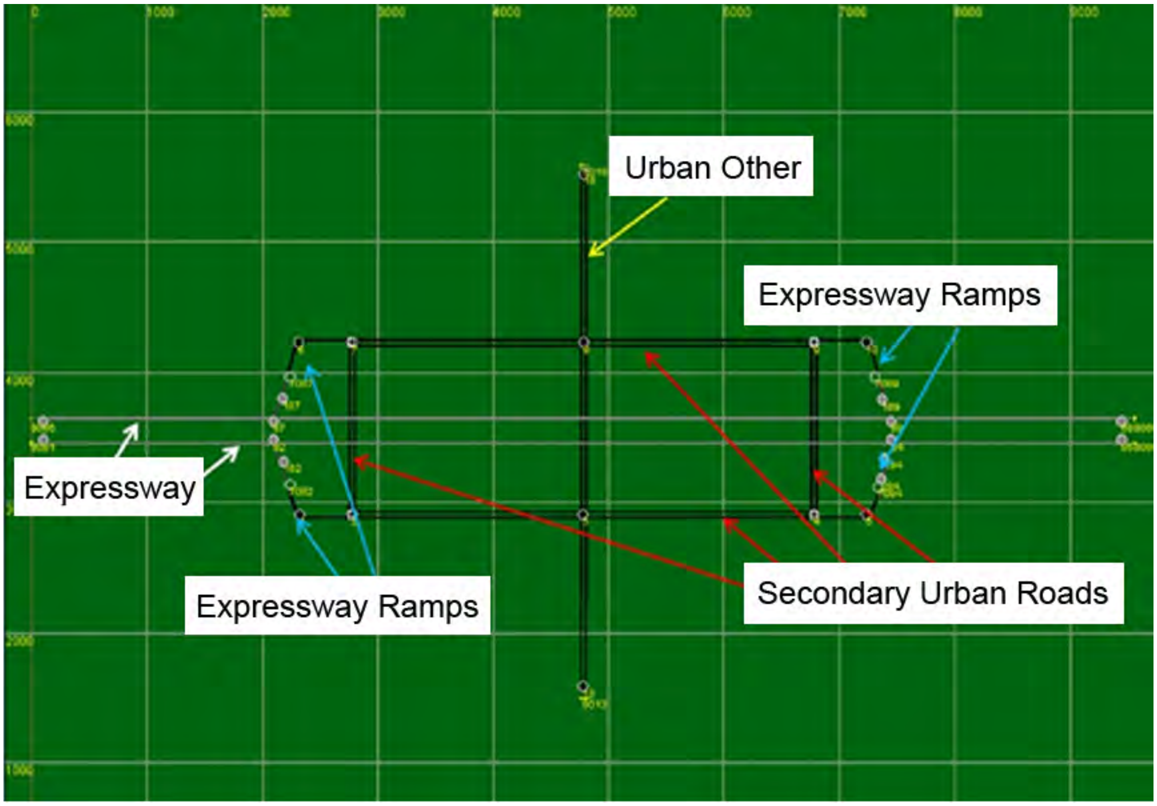


Figure 31. Urban Other

Lane closure simulation was subject to the NETSIM tool limitations with a maximum duration of 167 minutes for partial closures. Partial closure simulations alternated closing one direction of travel for 2 minutes and then opening the opposite direction during that time to mimic how a police officer would direct traffic around a crash scene on an undivided two-lane road. Full closures stop traffic in both directions of travel.

### 3.4.17 Rural Expressway

The Rural Expressway configuration mirrors the Urban Expressway with the exception that the roadway consists of two lanes of travel in each direction. Rubbernecking factors are adjusted according to Table 25 and traffic volumes were selected as 50 and 150 vph per direction of travel. Free-flow speeds were 65 mi/h, similar to Urban Expressways, and fleet mix consisted of 4 percent single trucks and 16 percent double unit trucks, based on HPMS data.

Full and partial closures are modeled in a manner similar to Urban Expressway scenarios. Partial closures remained as a single lane closed and a single lane open throughout the duration period.

### 3.4.18 Rural Other

Rural Other roadways (Collectors, and Local roads) are modeled similarly to the Urban Arterial network but there are no traffic signals at intersections. The link length for the Rural Other road where the crash occurs is increased to 1 mile to represent the increased distance between intersections for rural surface roads. The free-flow speed is 55 mi/h, and the percent truck mix is 5 percent for single unit and 4 percent for double unit, based on HPMS data.

Similar to the Urban Arterial and Urban Other scenarios, the Rural Other simulation network includes an expressway and connecting secondary surface roads. The connected roads have the following free-flow speed settings at 65 mi/h for the expressway and 55 mi/h for the connecting secondary roads based on HPMS data.

Rural Other lane closure is simulated with the same method as for Urban Other scenarios: alternating directions of travel open for partial closures and both sides blocked for full closures.

### 3.4.19 Traffic Simulation Outputs

TSIS-CORSIM provides a wide range of roadway and vehicle performance measures referred to as methods of effectiveness (MOEs). The key MOEs for this analysis are total vehicle delay hours and vehicle fuel consumption. Fuel consumption values of total consumption and the ratio of conventional gasoline to diesel consumed were used to calibrate the emissions modeling. Recall that each scenario was run several times (10 times for the baseline scenario and 40 times for each crash scenario). This analysis focuses on the median amount of vehicle delay across runs from a given scenario. Future research may involve analysis that incorporates the variance of the analytic results across simulation runs.

## 3.5 NETWORK DELAY

The second portion of delay that occurs on other facilities than the one on which the crash occurs is estimated by means of deterministic diversion and traffic backup models that intend to represent typical conditions for traffic that is rerouted as a result of the crash. Each road type has a separate model for network delay in the sense that the parameters are selected on the basis of data representing the applicable conditions. The diversion delay is also dependent upon the rules for determining when and how traffic is diverted from the crash facility as a function of the facility type and duration.

### 3.5.1 Diversion Model

The TSIS-CORSIM simulation model is used to estimate the amount of delay experienced by drivers traveling the road segment on which a given crash occurs (hereafter referred to as “main route delay”). However, some severe crashes may cause delay for drivers using alternate parallel routes (hereafter referred to as “alternate route delay”), which TSIS-CORSIM does not capture. Such alternate route delay would likely stem from main route drivers diverting around the site of the crash, thereby interacting with alternate route drivers. This type of diversion behavior would be expected from drivers trapped behind a long and slow-moving backup for two principal reasons. First, the rational response of a delayed driver would be to look for the closest alternate route, provided a familiarity with the surrounding streets. Second, many urban areas have developed detailed alternate route plans that are to be implemented by transportation officials or police in the event of a crash. Either cause of diversion would result in a fraction of drivers taking a more circuitous route on lower functional class roads. Hence, alternate route delay can be partitioned into three main components:

- Delay experienced by diverted main route travelers taking a more circuitous route.

- Delay experienced by diverted main route travelers driving on roads with lower speed limits.
- Congestion delay caused by diverted main route travelers interacting with alternate route drivers on lower capacity alternate routes.

To calculate delay stemming from crashes above a certain level of severity (as determined by duration and degree of lane-closure), a spreadsheet-based diversion delay model was also developed. The diversion delay model is based on deterministic queuing theory. This section describes the technical aspects of the model, the model parameters, and its resolution with the TSIS-CORSIM model.

### 3.5.2 Deterministic Queuing Model

The alternate route delay model is based on simple deterministic queuing theory. The model takes three key inputs:

- Dynamically-changing vehicle entry and exit rates for the main road segment.
- Constant vehicle entry and exit rates for the alternate road segment.
- The temporal pattern of the closure duration (i.e., the length of time it takes to partially or fully restore service levels on the main road segment).

As vehicles divert to the alternate route, a backup will form if the increased total volume of traffic exceeds the alternate route's capacity. The backup thereby leads to delay. In this model the physical length of the backup is ignored (it can be thought of as a vertical backup), while the extra driving distance required by diverted main route travelers is adjusted outside the traffic backup model.

The total vehicle entry rate ($V(t)$) changes over time (denoted by $t$) and depends on user-selected model parameters. Further, total vehicle entries equals the sum of the regular hourly volume of traffic on the alternate route ($Va$), plus the diverted volume of traffic from the main route ($Vm(t)$). As mentioned above, the alternate-route vehicle entry rate does not change throughout the duration of the closure, while the main route entry rate will change over time according to the conditions on the main route where the crash occurred. For example, vehicle volume on the alternate route prior to diversion is simply the normal alternate route traffic volume. After diversion begins (when $t = td$) the total volume (and entry rate) will equal the sum of the alternate and main volume. Similarly, after the crash on the main route is cleared and traffic is no longer diverted (when $t = tc$), the total volume of traffic entering the alternate route will revert to the normal alternate volume.

The exit rate in the diversion model ($X(t)$) is equal to the sum of the available capacity on the main and alternate routes, ($Xm(t)$ and $Xa$ respectively). For example, immediately after a full closure crash, the total exit rate in the backup model is simply equal to the hourly capacity of the alternate route (because the main exit rate is zero). However, once the crash is fully cleared, the exit rate will equal the sum of the applicable hourly capacity on the main route plus the hourly capacity of the alternate route.

Together, the entry and exit rates determine the total amount of time it takes the two routes to serve all of the traffic volume. Note that the backup clears when the number of cumulative exits equals the number of cumulative entries. The formula used to calculate the amount of congestion delay is:

$$\text{Backup Delay (t)} = \int_{\text{Backup Formation}}^{\text{Backup Dissipation}} (V_m(z) + V_a(z) - X_m(z) - X_a(z))dz$$

**Figure 32. Equation. Formula Used to Calculate the Amount of Congestion Delay**

Note that *z* is the variable of integration and the time variable (*t*) is embedded in the limits of integration.

Intuitively, the delay calculation can be illustrated using cumulative entry and exit curves, as seen in Figure 34. Note that the total amount of delay is equal to the shaded area between the cumulative entry curve and the cumulative exit curves.

In addition to calculating backup-related delay, as described above, the model also calculates additional crash-induced travel time for diverted travelers. Such additional travel time would be experienced by diverted drivers that opt to take a slower more circuitous route (relative to the route they would have taken in the absence of a crash). The additional delay is a function of the traffic speed on the main route ($S_m$), the traffic speed on the alternate route ($S_a$), the extra diversion distance (*d*), and the number of diverted main route travelers. If the alternate route length is given by $L_a$ and the main route length is given by $L_m$, then the travel time delay function is:

$$\text{Travel Time Delay} = \frac{V_m \times (t_c - t_d) \times L_a}{S_a} - \frac{V_m \times (t_c - t_d) \times L_m}{S_m}$$

**Figure 33. Equation. Formula to Calculate Travel Time Delay**

So the entire amount of delay time simply equals the sum of backup delay and travel time delay.

### 3.5.3 Model Parameters

This section presents the parameters used by the model to calculate diversion delay. The parameters for each scenario are shown in Table 26. The first column describes the roadway type, the entry rate of vehicles onto the main road, which is actually the volume of traffic in one direction that is specified for the scenario. The third column is the exit rate for the roadway, or its capacity. HPMS data shows that volume is roughly 2,000 vph per lane of roadway. The HPMS data also informed the choice of free-flow speeds for the main roadways. These speeds are also specified in the TSIS-CORSIM work (see

Table 16). The speeds of the alternate routes are speeds specified for the next lower roadway type. The alternate routes for the lowest roadway type is the same as the main route type. The additional distance measures were calculated from a variety of sources. For urban roads and Rural Interstates, the diversion distance was based on the distance between off ramps from a sample of Urban Interstates. For other rural roads, a random sample of 30 crashes was selected from the Pennsylvania crash database. The latitude and longitude of these crashes were entered into a mapping program, which then calculated the closest diversion distance. The average detour length of the 30 random crashes is used here.

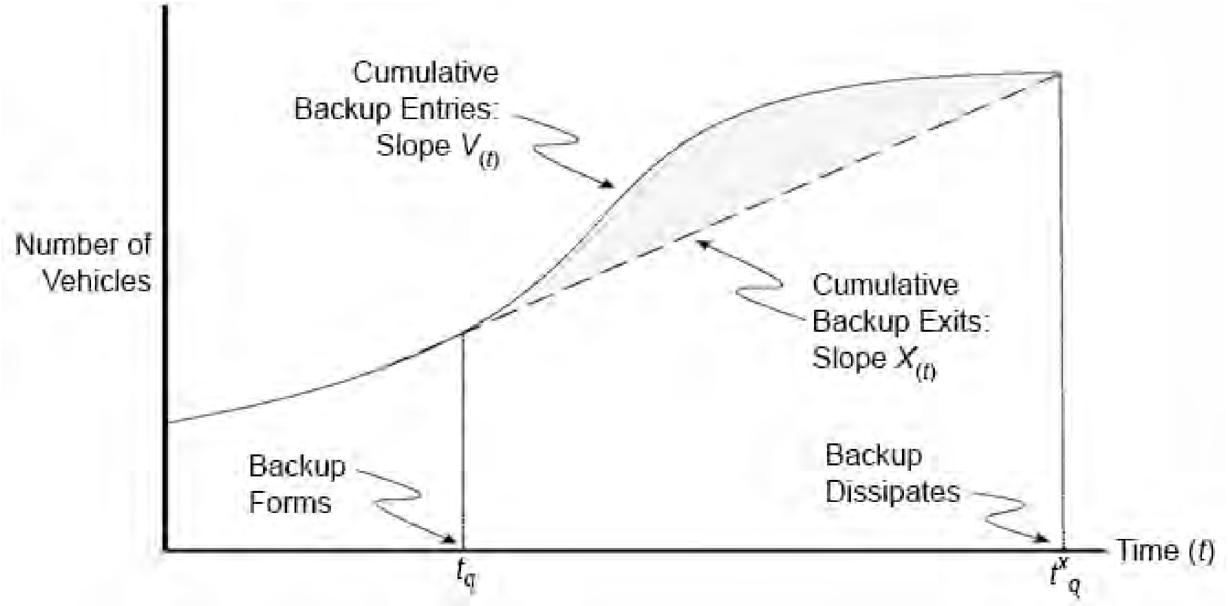


Figure 34. Deterministic Queuing

Finally, the time to diversion was based on evidence in a 1999 report by the National Cooperative Highway Research Program (Dunn et al., 1999).

## 3.6 EXAMPLE OUTPUT

The spreadsheet model was designed to accommodate a wide range of plausible parameter estimates, in order to test the model sensitivity to inputs. Figure 35 illustrates the cumulative entry and exit rate curves for the following scenario: Urban Expressway, full closure, 4-hour duration, 3,000 vph entry rate. The backup delay value was calculated using the equation shown in Figure 32. A separate section of the model calculated the extra travel time due to slower free-flow speeds and extra diversion distance.

**Table 26. Diversion Model Parameters**

| Roadway Type | Main Entry Rate (vph) | Main Exit Rate (vph) | Main Entry Free-Flow Speed (mi/h) | Alt. Entry Rate (vph) | Alt. Exit Rate (vph) | Alt. Free-Flow Speed (mi/h) | Additional Distance (Miles) | Time to Diversion | Partial Opening After (Hours) | Full Opening After (Hours) |
|---|---|---|---|---|---|---|---|---|---|---|
| Urban Interstate/ Expressway | 3,000 | 6,000 | 60 | 2,000 | 4,000 | 45 | 1.00 | 1.00 hour | 2.0 | 4.0 |
| Urban Interstate/ Expressway | 2,000 | 6,000 | 60 | 2,000 | 4,000 | 45 | 1.00 | 1.00 hour | 2.0 | 4.0 |
| Urban Interstate/ Expressway | 1,000 | 6,000 | 60 | 2,000 | 4,000 | 45 | 1.00 | 1.00 hour | 2.0 | 4.0 |
| Urban Arterial | 1,000 | 4,000 | 45 | 300 | 2,000 | 30 | 1.00 | 1.00 mi. queue | | 1.5 |
| Urban Arterial | 1,000 | 4,000 | 45 | 300 | 2,000 | 30 | 1.00 | 1.00 mi. queue | 2.0 | 4.0 |
| Urban Arterial | 500 | 4,000 | 45 | 150 | 2,000 | 30 | 1.00 | 1.00 mi. queue | | 1.5 |
| Urban Arterial | 500 | 4,000 | 45 | 150 | 2,000 | 30 | 1.00 | 1.00 mi. queue | 2.0 | 4.0 |
| Urban Other | 300 | 2,000 | 30 | 300 | 2,000 | 35 | 1.00 | 0.25 mi. queue | | 1.5 |
| Urban Other | 300 | 2,000 | 30 | 300 | 2,000 | 35 | 1.00 | 0.25 mi. queue | 2.0 | 4.0 |
| Urban Other | 150 | 2,000 | 30 | 150 | 2,000 | 35 | 1.00 | 0.25 mi. queue | | 1.5 |
| Urban Other | 150 | 2,000 | 30 | 150 | 2,000 | 35 | 1.00 | 0.25 mi. queue | 2.0 | 4.0 |
| Rural Interstate/ Principal Arterial | 1,000 | 4,000 | 65 | 300 | 2,000 | 55 | 4.15 | 1.00 hour | 2.0 | 4.0 |
| Rural Interstate/ Principal Arterial | 500 | 4,000 | 65 | 100 | 2,000 | 55 | 4.15 | 1.00 hour | 2.0 | 4.0 |
| Rural Other | 150 | 2,000 | 55 | 150 | 2,000 | 55 | 5.70 | 0.75 hours | 1.5 | 1.5 |
| Rural Other | 150 | 2,000 | 55 | 150 | 2,000 | 55 | 5.70 | 1.00 hour | 2.0 | 4.0 |
| Rural Other | 50 | 2,000 | 55 | 50 | 2,000 | 55 | 5.70 | 0.75 hours | 1.5 | 1.5 |
| Rural Other | 50 | 2,000 | 55 | 50 | 2,000 | 55 | 5.70 | 1.00 hour | 2.0 | 4.0 |

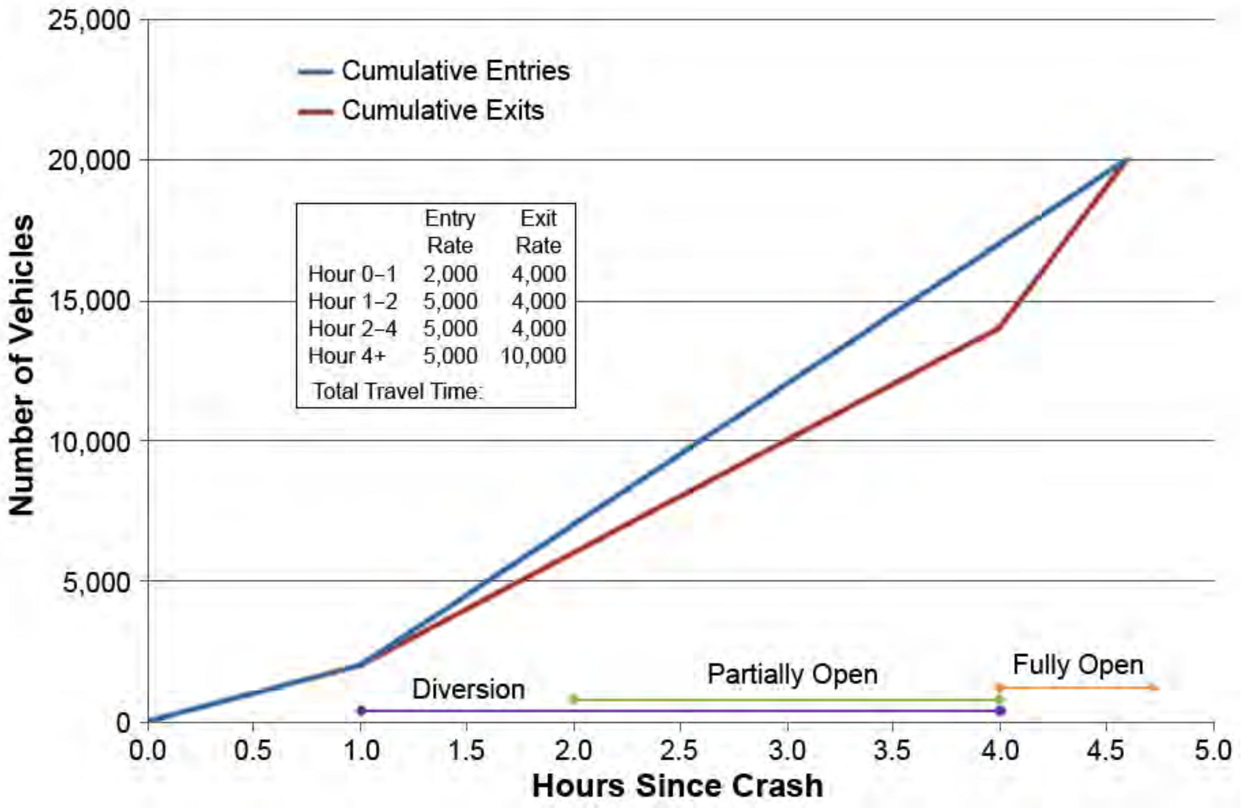


**Figure 35. Example of Alternate Route Delay**
**(Urban Expressway, Full Closure, Unidirectional Volume = 3,000 vph)**

The amount of delay calculated by the diversion model for each applicable scenario was then added to the values generated by TSIS-CORSIM. Note that in some scenarios, the cumulative number of entries never exceeds the cumulative number of exits. Hence, diversion delay will be zero for some scenarios, but the model will still calculate the delay due to slower free-flow speeds and longer routes.

### 3.6.1 Delay Extrapolation

The TSIS-CORSIM model was used to model crash delay for closures less than or equal to 240 minutes. However, there is a nontrivial number of crashes with longer durations. In order to model crashes lasting longer than 240 minutes, a queuing model similar to the one used to model arterial diversion was developed. The long-duration model also is based upon deterministic queuing theory, and the only difference between the two queuing models is the parameter defining the rate of entry onto the main route. For the long-duration scenarios (420- and 540-minute closures), the main and alternate rates of entry did not stay constant throughout the closure. Instead, the entries tapered off after 4 hours at a rate determined by the daily distribution of traffic volume. This change to the model reflects the fact that the underlying demand for travel would tend to decline over time; the decline would occur for two primary reasons. First, demand would decline because some portion of travelers would be alerted to the crash (through the Internet, TV, or radio) and would shift their trip to another time or place. Second, as can be seen in the daily traffic distribution charts in Figure 27, traffic tends to taper off after the afternoon peak period. (For these scenarios, we assume that the crash occurred just to the right of the afternoon peak). Figure 36 illustrates the output from the modified version of the diversion model.

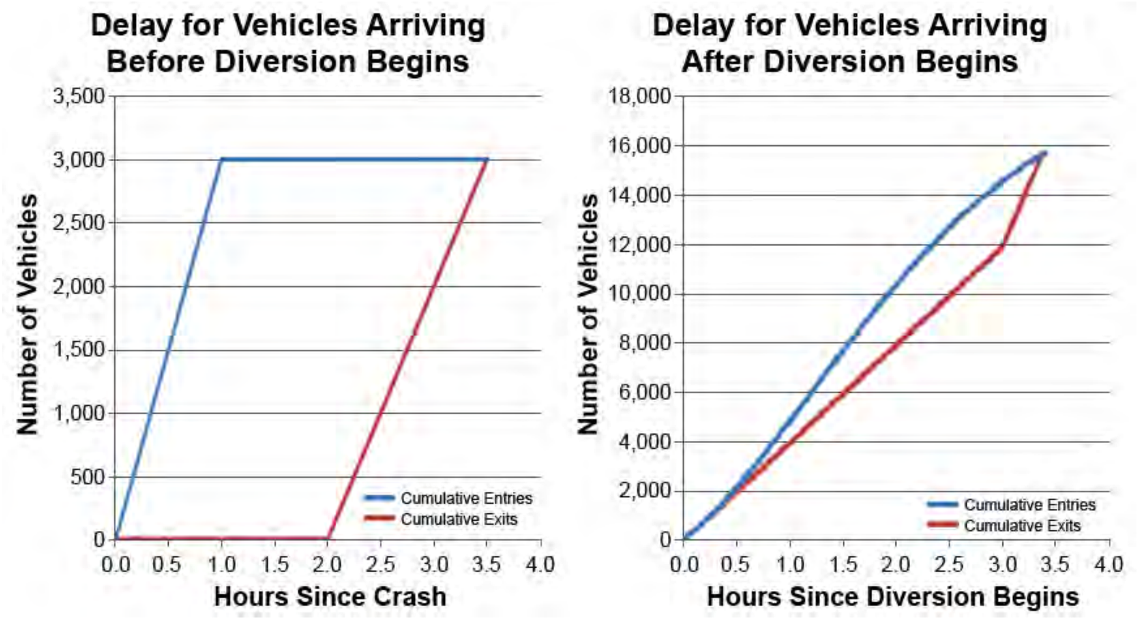
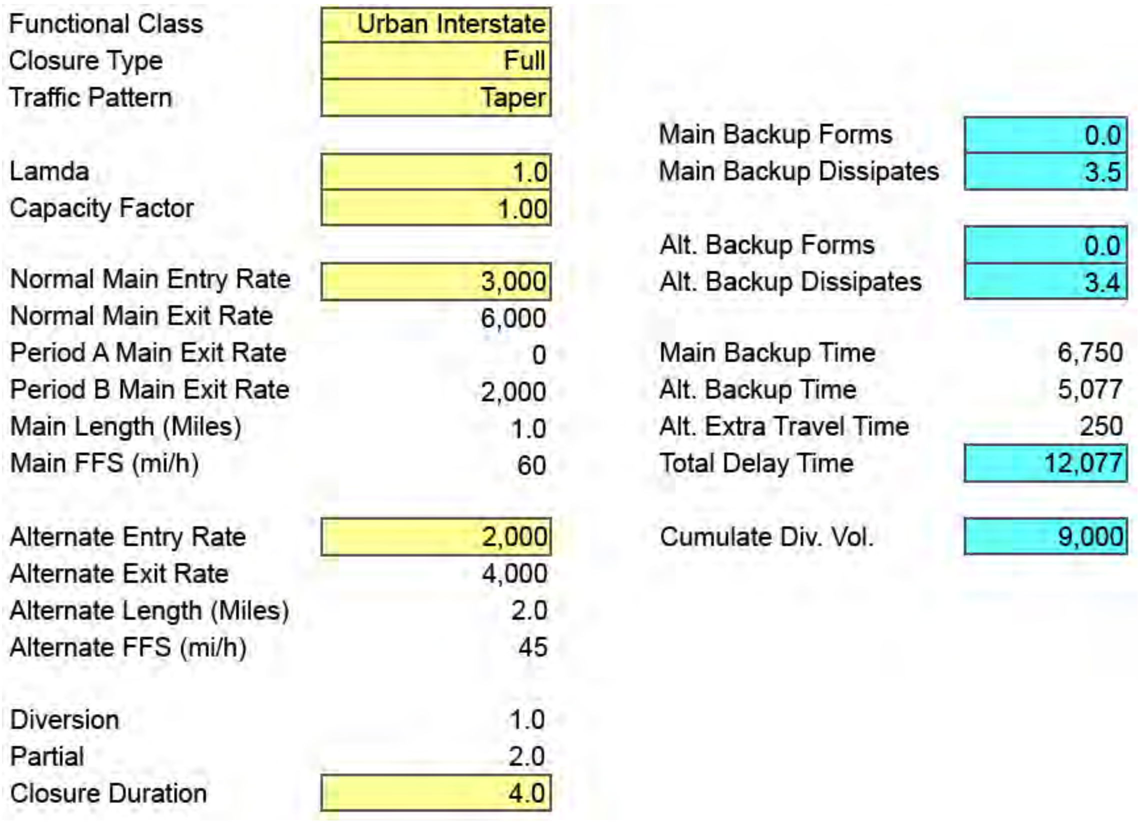


**Figure 36. Example of Delay Extrapolation Model for Urban Interstate/Expressway, 6-Hour Full Closure, Unidirectional Volume = 3,000**

Note that the model separately calculates the main route drivers' delay prior to diversion and total post-diversion delay independently. Also note that post-diversion, the total capacity and volume equals the sum of route specific capacities.

The parameters used in the scenario for Figure 36 are presented in Figure 36, and correspond to the Urban Expressway 240-minute full closure with an initial main entry rate of 3,000 vph. The model yielded very similar values to those obtained using the delay calculated from TSIS-CORSIM and the diversion model.

Figure 36 shows a graph of the output from each of the models. The red line represents the total delay calculated by TSIS-CORSIM and the diversion model, the green line represents the deterministic queuing replication of the TSIS- CORSIM model, and the blue line represents the extrapolation. Note, that the replication model closely replicated the output from TSIS-CORSIM and the diversion model. The same model is used to generate delay estimates for the other scenarios.



| | | | |
|---|---|---|---|
| Functional Class | Urban Interstate | | |
| Closure Type | Full | | |
| Traffic Pattern | Taper | | |
| | | Main Backup Forms | 0.0 |
| Lamda | 1.0 | Main Backup Dissipates | 3.5 |
| Capacity Factor | 1.00 | | |
| | | Alt. Backup Forms | 0.0 |
| Normal Main Entry Rate | 3,000 | Alt. Backup Dissipates | 3.4 |
| Normal Main Exit Rate | 6,000 | | |
| Period A Main Exit Rate | 0 | Main Backup Time | 6,750 |
| Period B Main Exit Rate | 2,000 | Alt. Backup Time | 5,077 |
| Main Length (Miles) | 1.0 | Alt. Extra Travel Time | 250 |
| Main FFS (mi/h) | 60 | Total Delay Time | 12,077 |
| Alternate Entry Rate | 2,000 | Cumulate Div. Vol. | 9,000 |
| Alternate Exit Rate | 4,000 | | |
| Alternate Length (Miles) | 2.0 | | |
| Alternate FFS (mi/h) | 45 | | |
| Diversion | 1.0 | | |
| Partial | 2.0 | | |
| Closure Duration | 4.0 | | |

**Figure 37. Parameters Applied to Model in Figure 22**

### 3.6.2 Results of Microsimulation and Diversion Models Combined

The total net delay for each scenario is displayed in Table 27. The vehicle delay listed is net of baseline vehicle delay and is the sum of delay along the main route with the crash and the delay from the adjoining road network as traffic diverts around the crash. As one would expect, vehicle delay increases with volume and duration of road closure. However, there are some anomalies worth discussing explicitly.

The net delay for some simulations is recorded as negative. The most egregious example of this is simulation 57. This represents a simulated Rural Interstate with unidirectional volume of 1,000 vph. There is no road closure for this simulation. The net delay in this case is -6 vehicle hours. This is due to the combination of two factors: random variation and excess capacity.

As discussed in previous sections, Monte Carlo simulation was used to produce the estimated delay results. The random variation introduced by this procedure may result in negative net delay when the impact of the random parameters is large relative to the total delay amount. This is potentially a problem for those simulation scenarios that have a combination of no or low duration closures or low volume to capacity ratios. These “at risk” scenarios will tend to be those with no road closure and on roadway types with extremely low volumes.

The presence of excess capacity also plays into these low or negative net delay numbers. The capacity of each lane was fixed within each simulation. Thus if the volume present during the simulation did not exceed the capacity of the open lanes, the delay estimated will also tend to be lower. A good example of this phenomenon is simulation 21. This represents an Urban Interstate with 2,000 vph in unidirectional volume. There is a partial closure that lasts for 4 hours. The net delay is 14 vehicle hours. Here, the partial closure does not restrict capacity sufficiently to result in a large delay estimate.

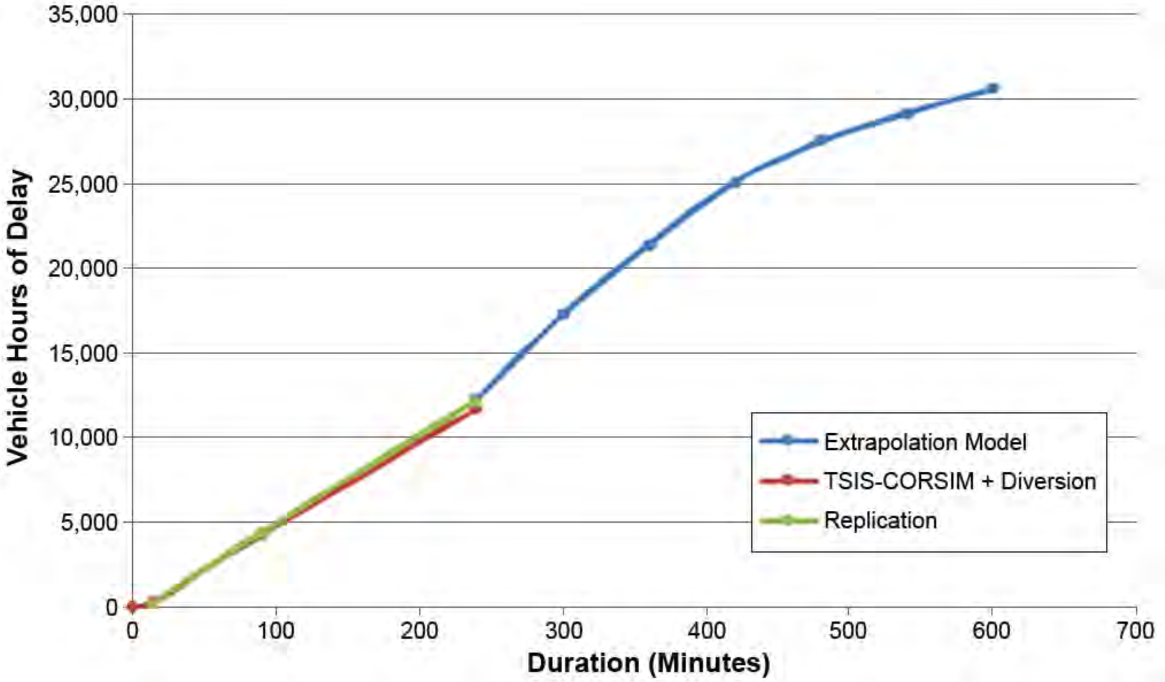


**Figure 38. Comparison of Results Between Delay Models (Urban Expressway, Volume = 3,000 vph)**

## Table 27. Simulation Scenarios

| Simulation Number | Roadway Type | Bi-Directional Volume | Closure Duration (Minutes) | Closure Type | Net Delay |
|---|---|---|---|---|---|
| 1 | Urban Interstate/Expressway | 6,000 | 0 | none | 0.2 |
| 2 | Urban Interstate/Expressway | 6,000 | 15 | full | 211.2 |
| 3 | Urban Interstate/Expressway | 6,000 | 90 | full | 4246.2 |
| 4 | Urban Interstate/Expressway | 6,000 | 240 | full | 11410.9 |
| 5 | Urban Interstate/Expressway | 6,000 | 15 | partial | 80.8 |
| 6 | Urban Interstate/Expressway | 6,000 | 90 | partial | 2963.6 |
| 7 | Urban Interstate/Expressway | 6,000 | 240 | partial | 5020.5 |
| 8 | Urban Interstate/Expressway | 4,000 | 0 | none | 0.3 |
| 9 | Urban Interstate/Expressway | 4,000 | 15 | full | 102.8 |
| 10 | Urban Interstate/Expressway | 4,000 | 90 | full | 2416.3 |
| 11 | Urban Interstate/Expressway | 4,000 | 240 | full | 3382.5 |
| 12 | Urban Interstate/Expressway | 4,000 | 15 | partial | 27.7 |
| 13 | Urban Interstate/Expressway | 4,000 | 90 | partial | 1023.5 |
| 14 | Urban Interstate/Expressway | 4,000 | 240 | partial | 1701.8 |
| 15 | Urban Interstate/Expressway | 2,000 | 0 | none | -0.1 |
| 16 | Urban Interstate/Expressway | 2,000 | 15 | full | 45 |
| 17 | Urban Interstate/Expressway | 2,000 | 90 | full | 827.7 |
| 18 | Urban Interstate/Expressway | 2,000 | 240 | full | 766.1 |
| 19 | Urban Interstate/Expressway | 2,000 | 15 | partial | -0.3 |
| 20 | Urban Interstate/Expressway | 2,000 | 90 | partial | 7 |
| 21 | Urban Interstate/Expressway | 2,000 | 240 | partial | 14 |
| 22 | Urban Arterial | 2,000 | 0 | none | 0 |
| 23 | Urban Arterial | 2,000 | 15 | full | 99.12 |
| 24 | Urban Arterial | 2,000 | 90 | full | 458.91 |
| 25 | Urban Arterial | 2,000 | 240 | full | 914.02 |
| 26 | Urban Arterial | 2,000 | 15 | partial | 19.03 |
| 27 | Urban Arterial | 2,000 | 90 | partial | 114.19 |
| 28 | Urban Arterial | 2,000 | 240 | partial | 304.51 |
| 29 | Urban Arterial | 1,000 | 0 | none | 0 |
| 30 | Urban Arterial | 1,000 | 15 | full | 43.64 |
| 31 | Urban Arterial | 1,000 | 90 | full | 195.4 |
| 32 | Urban Arterial | 1,000 | 240 | full | 364.27 |
| 33 | Urban Arterial | 1,000 | 15 | partial | 13.15 |
| 34 | Urban Arterial | 1,000 | 90 | partial | 32.58 |
| 35 | Urban Arterial | 1,000 | 240 | partial | 86.88 |
| 36 | Urban Other | 600 | 0 | none | 0 |
| 37 | Urban Other | 600 | 15 | full | 46.33 |
| 38 | Urban Other | 600 | 90 | full | 369.3 |
| 39 | Urban Other | 600 | 240 | full | 813.99 |
| 40 | Urban Other | 600 | 15 | partial | 1.71 |
| 41 | Urban Other | 600 | 90 | partial | 8.54 |

| Simulation Number | Roadway Type | Bi-Directional Volume | Closure Duration (Minutes) | Closure Type | Net Delay |
|---|---|---|---|---|---|
| 42 | Urban Other | 600 | 240 | partial | 22.77 |
| 43 | Urban Other | 300 | 0 | none | 0 |
| 44 | Urban Other | 300 | 15 | full | 24.72 |
| 45 | Urban Other | 300 | 90 | full | 253.14 |
| 46 | Urban Other | 300 | 240 | full | 590.55 |
| 47 | Urban Other | 300 | 15 | partial | 0.94 |
| 48 | Urban Other | 300 | 90 | partial | 5.29 |
| 49 | Urban Other | 300 | 240 | partial | 14.11 |
| 50 | Rural Interstate/Principal Arterials | 2,000 | 0 | none | 0 |
| 51 | Rural Interstate/Principal Arterials | 2,000 | 15 | full | 67.79 |
| 52 | Rural Interstate/Principal Arterials | 2,000 | 90 | full | 919.67 |
| 53 | Rural Interstate/Principal Arterials | 2,000 | 240 | full | 768.03 |
| 54 | Rural Interstate/Principal Arterials | 2,000 | 15 | partial | 26.58 |
| 55 | Rural Interstate/Principal Arterials | 2,000 | 90 | partial | 27.22 |
| 56 | Rural Interstate/Principal Arterials | 2,000 | 240 | partial | 28.83 |
| 57 | Rural Interstate/Principal Arterials | 1,000 | 0 | none | -6 |
| 58 | Rural Interstate/Principal Arterials | 1,000 | 15 | full | 18.49 |
| 59 | Rural Interstate/Principal Arterials | 1,000 | 90 | full | 257.43 |
| 60 | Rural Interstate/Principal Arterials | 1,000 | 240 | full | 360.07 |
| 61 | Rural Interstate/Principal Arterials | 1,000 | 15 | partial | 0.1 |
| 62 | Rural Interstate/Principal Arterials | 1,000 | 90 | partial | 0.2 |
| 63 | Rural Interstate/Principal Arterials | 1,000 | 240 | partial | 0.55 |
| 64 | Rural Other | 300 | 0 | none | 0 |
| 65 | Rural Other | 300 | 15 | full | 8.74 |
| 66 | Rural Other | 300 | 90 | full | 101.03 |
| 67 | Rural Other | 300 | 240 | full | 273.67 |
| 68 | Rural Other | 300 | 15 | partial | 0.57 |
| 69 | Rural Other | 300 | 90 | partial | 9.29 |
| 70 | Rural Other | 300 | 240 | partial | 27.77 |
| 71 | Rural Other | 100 | 0 | none | 0 |
| 72 | Rural Other | 100 | 15 | full | 4.58 |
| 73 | Rural Other | 100 | 90 | full | 45.11 |
| 74 | Rural Other | 100 | 240 | full | 104.36 |
| 75 | Rural Other | 100 | 15 | partial | 0.33 |
| 76 | Rural Other | 100 | 90 | partial | 2.97 |
| 77 | Rural Other | 100 | 240 | partial | 7.92 |

### 3.6.3 Estimating Delay as a Function of Volume and Duration

Due to computational constraints, only a finite number of simulations are performed. This section describes the process of estimating a function based on the subset of scenarios run, that can return generalized estimates of expected vehicle delay given a roadway type, volume and duration. The data used for the estimates are displayed in Table 27. The delay estimates for partial and full duration for certain roadway type, volume and duration are combined into a single delay estimate using a frequency weighted average. Separate surfaces were fit for partial and full closures, but resulted in surfaces that were unacceptable in terms of smoothness and shape. These data points are used to parameterize the following sigmoid functional form (Figure 39) which returns total vehicle delay as a function of volume and duration:[16]

$$\text{Delay} = a + b \times \frac{1}{1 + e^{-\left(\frac{\text{volume} - c}{d}\right)}} \times \frac{1}{1 + e^{-\left(\frac{\text{duration} - e}{f}\right)}}$$

**Figure 39. Equation. Formula to Determine Total Vehicle Delay**

where *a*, *b*, *c*, *d*, and *f* are parameters chosen for goodness of fit. This functional form exhibits certain desirable properties: it is monotonically increasing in both volume and duration, it is smooth, it has no singularities, and it allows for fitting an "S" shape to the three dimensional curve.

A surface of this shape is estimated for each roadway type using the software package TableCurve 3D by Systat. The parameters for each roadway type are displayed in Table 28.

**Table 28. Sigmoid Parameters**

| Functional Class | a | b | c | d | e | F |
|---|---|---|---|---|---|---|
| Urban Interstate/Expressway | -208.513 | 48,250.17 | 6,458.094 | 1,508.643 | 287.2916 | 108.8223 |
| Urban Arterial | -54.0935 | 15,215.42 | 4,479.63 | 1,785.987 | 417.3425 | 133.7807 |
| Urban Other | 9.564185 | 945.1581 | 301.0674 | 11.11572 | 258.8092 | 91.85911 |
| Rural Interstate or Principal Arterial | 85.4214 | 2,656.267 | 988.0198 | 120.887 | 381.4386 | 72.88288 |
| Rural Other | -4.8833 | 654.6301 | 185.057 | 84.79895 | 365.8839 | 123.8583 |

## 3.7 CRASH FREQUENCY

### 3.7.1 Probability of Crash Duration

In section 3.6.3, the estimates from partial and full closure scenarios were combined to estimate a single function. The Pennsylvania data describing the probability that a crash of a certain severity (fatal, injury only, and PDO) will have a certain duration of road closure also needs to be combined across partial and full closures to yield appropriate probability estimates to combine

---

[16] Other "S"-shaped surfaces, such as one based on a cumulative Gaussian form, produce very similar results in terms of the fit of the data and overall shape and curvature of the estimated surfaces.

with the results of the delay function estimation. Those data are presented in Table 29. These frequency weights are applied to the estimated matrix of vehicle hours of delay. This results in a series of estimates that are conditional on severity and time of day. The next section outlines how the time of day dimension is further collapsed to remove the time of day dependence.

**Table 29. Probability of Various Closure Durations by Severity**

| **Bin** | **No Closure** | **0-30 min** | **30-60 min** | **1-3 hrs** | **3-6 hrs** | **6-9 hrs** | **>9 hrs** |
|---|---|---|---|---|---|---|---|
| **Median Closure** | **0 min** | **15 min** | **45 min** | **90 min** | **4 hrs** | **7 hrs** | **9 hrs** |
| Fatal | 7% | 1% | 4% | 30% | 37% | 13% | 8% |
| Injury Only | 38% | 15% | 23% | 16% | 6% | 2% | 1% |
| PDO | 50% | 15% | 18% | 12% | 4% | 1% | 0% |
| **All** | **47%** | **15%** | **18%** | **13%** | **5%** | **1%** | **1%** |

### 3.7.2 Probability of Crash by Hour

The probability of a crash of certain severity occurring in a certain hour type ($\Pr_s(crash_h)$) is computed from the FARS database for fatal crashes and the GES database for injury only and PDO crashes. Recall that both of those crash databases contain time of day and day of week descriptors for each crash. The probabilities are calculated for each hour of the day (1–24) for weekdays and weekends separately. The severity-specific probabilities are show in Table 30. These frequencies are applied to the estimated delay numbers after the duration frequency weights have been applied, providing vehicle hours of delay estimates by road type and severity.

The distribution of crashes by hour differs greatly between weekends and weekdays. The weekend distributions are much flatter throughout the day compared with the weekday distributions. The weekday distributions exhibit similar variation across time of day to the volume profiles. Fatal crash rates for weekday mornings appear relatively high when compared with the volume. This trend does not continue throughout the day. PDO and Injury crashes appear to be in line with volume in the morning and evening, but in the middle of the day appear to be more frequent than the volume would suggest. Recall that the crash distribution is for crashes involving a truck while the volume profile includes all vehicles. Thus, the differences in the distributions could be a function of different daily behavior of truck drivers compared with the overall population. On the other hand, the distributional differences might be a function of other characteristics, such as fatigue. A more rigorous comparison of the distributions is needed to investigate the causes of the differences in the distributions.

**Table 30. Hourly Crash Frequencies by Severity**

| Hour | Weekday Fatal | Weekday Injury | Weekday PDO | Weekend Fatal | Weekend Injury | Weekend PDO |
|---|---|---|---|---|---|---|
| 1 | 1.98% | 0.80% | 1.05% | 3.60% | 2.78% | 3.19% |
| 2 | 2.07% | 0.98% | 0.81% | 4.95% | 4.03% | 2.46% |
| 3 | 2.42% | 0.96% | 0.56% | 6.19% | 1.84% | 3.09% |
| 4 | 2.04% | 0.79% | 0.71% | 4.95% | 4.65% | 1.96% |
| 5 | 2.28% | 1.22% | 1.00% | 3.85% | 2.74% | 2.24% |
| 6 | 3.80% | 2.18% | 1.49% | 5.09% | 3.02% | 2.38% |
| 7 | 5.59% | 3.23% | 3.21% | 3.85% | 2.98% | 2.35% |
| 8 | 5.44% | 6.79% | 5.63% | 3.65% | 3.57% | 4.05% |
| 9 | 5.25% | 7.14% | 7.68% | 3.65% | 6.43% | 3.38% |
| 10 | 5.56% | 6.85% | 7.45% | 3.50% | 3.83% | 6.81% |
| 11 | 6.04% | 6.99% | 6.22% | 4.10% | 6.47% | 7.02% |
| 12 | 6.16% | 6.37% | 8.16% | 4.55% | 7.48% | 4.30% |
| 13 | 5.55% | 7.75% | 7.31% | 4.75% | 4.61% | 4.36% |
| 14 | 6.78% | 8.49% | 7.60% | 4.25% | 6.38% | 5.95% |
| 15 | 6.82% | 8.39% | 7.47% | 6.14% | 2.83% | 5.65% |
| 16 | 6.62% | 7.39% | 7.87% | 3.60% | 3.84% | 5.12% |
| 17 | 5.29% | 6.25% | 6.95% | 4.15% | 4.71% | 7.64% |
| 18 | 4.32% | 4.75% | 6.06% | 3.30% | 4.96% | 4.68% |
| 19 | 3.62% | 3.28% | 4.29% | 3.95% | 6.22% | 6.34% |
| 20 | 2.46% | 2.23% | 2.05% | 4.35% | 4.23% | 3.98% |
| 21 | 2.88% | 1.96% | 1.66% | 3.35% | 2.96% | 2.36% |
| 22 | 2.43% | 1.96% | 1.79% | 2.90% | 5.61% | 3.73% |
| 23 | 2.18% | 1.65% | 1.55% | 3.90% | 1.52% | 3.01% |
| 24 | 2.42% | 1.61% | 1.44% | 3.50% | 2.33% | 3.96% |

## 3.8 OCCUPANCY AND THE VALUE OF TRAVEL TIME

The time spent in travel is treated as a cost to the user. Because the purpose of transportation investment is to reduce the amount of time—and other costs—required to move people and goods from place to place, there is a tradeoff between construction and facility operation, on the one hand, and the amount of time saved on the other. Thus it is hard to avoid the need to place dollar values on both sides in order to estimate what expenditures are worth making in order to save travel time.

Fundamentally, the VOT savings is an opportunity cost, in that the time could be used for something else. Thus it must be worth at least as much as the value of the activity given up in order to travel. The alternative activity could be leisure or work. Work time is reasonably valued at the worker’s wage rate, reflecting the employer’s valuation of the time. Leisure time is typically valued at a lower rate per hour, perhaps on the assumption that less effort is required, or that employment opportunities for the additional hours are not available to the traveler.

### 3.8.1 Wage Rate

The traveler's wage rate is commonly taken as the upper bound for the value of travel time, although there certainly could be instances in which waiting in traffic is more onerous than simply not being able to work, because of frustration and discomfort. In practice, paid time or commercial time is valued at the wage rate, while commute and leisure time is assigned a lower value, typically one-half the wage rate.

Both vehicles and inventory have opportunity costs that occur from being stuck in traffic. Vehicles may have other users and uses, which are deferred if the vehicle is not available. Cargo may also have a time value—perishability or subsequent usage—that represents the willingness to pay (WTP) of the owner for receiving the cargo at a particular time.

### 3.8.2 Disutility

Another component of VOT is discomfort. Given that the traveler's preferred condition is to be comfortable, a travel situation that is uncomfortable is more costly to the user than it would be if it were pleasant. Time spent standing on a crowded train is more painful, and therefore more costly, than the same time seated comfortably. The productivity component (the amount of preferred activity that is given up) and the discomfort component (the user's valuation of the discomfort) can be added together to get the opportunity cost of travel time.

Because the conditions and preferences for each traveler are mostly unknown, numerous shortcuts are necessary to obtain user empirical estimates of VOT. Average wage rates can be taken from published statistics, and evidence of willingness to pay extracted from situations where users have a choice of paying additional money to obtain faster travel. Work versus personal travel can be imputed from vehicle type, based on surveys.

There are many ways to construct an average value of time, and the average values can be applied at a disaggregate (e.g., by vehicle type and location) or aggregate (a single global average). One possible process will be described below, including the translation from individual value of time to the cost of vehicle hours of delay.

### 3.8.3 Empirical Estimation

USDOT guidance recommends the method of pegging the opportunity cost of travel time to a fraction of the wage rate (USDOT, 2003). The individual hourly rates in Table 31 have been constructed using Bureau of Labor Statistics data for total national employment compensation and truck operator wage rates. The right-hand column shows the calculated VOT values for three categories of individual travel times.

**Table 31. Individual VOT Estimates (2010 Dollars)**

| | Wage Rate* | Benefits Percent† | VOT % of Wage‡ | VOT |
|---|---|---|---|---|
| Personal | 22.59 | 25% | 50% | 14.12 |
| Business | 22.59 | 25% | 100% | 28.24 |
| Truck Operator | 18.87 | 30% | 100% | 24.53 |

* Wage rate for all workers taken from Bureau of Labor Statistics (BLS) tables (http://data.bls.gov/cgi-bin/srgate, Series CES0500000003 and http://www.bls.gov/oes/2009/may/oes533032.htm#nat).

† Estimated

‡ Assumed; DOT guidance recommends 100% for business travel and 35-60% for local personal travel

With these basic rates, vehicle VOT rates can be calculated based on vehicle types, occupancies, and shares of business versus personal travel. The framework used in FHWA's Highway Economic Requirements System (HERS) model is shown in Table 32. Values per vehicle hour of delay in the bottom row vary across the vehicle classes because of differences in the rate of business use and occupancy levels.

### 3.8.4 Aggregation to Global Averages

These hourly rates by vehicle classes can be aggregated into a global average by weighting them according to each class's share of total VMT. As long as the mix of traffic and crashes doesn't change among road types, the global average remains applicable. Alternatively, if the mix of crashes is to be focused on particular road types, for regulatory reasons, then the average VOT may change depending upon the locations of crashes of interest. The difference would be small relative to other sources of imprecision—including the individual values of time and the mix of trip purposes— but acknowledging the different mixes of vehicles in the incident queues could be of interest in some contexts. This level of disaggregation was not used for the present study, but could easily be incorporated in future research.

To illustrate the method for step-wise aggregation, the distribution of vehicle types within the three classes in the crash cost analysis—passenger cars, single unit trucks, and combination trucks—can be taken from HERS data. These distributions apply to functional classes as a whole, not to individual road sections, so they are assumed to be fixed for a given road type. The HERS data are summarized in Table 33. Entries in the same row between bar lines sum to 100 percent, e.g., the Small Auto category is 25 percent of the Passenger Car group on the Urban Interstates and Expressways road type.

### Table 32. Vehicle Classes, Occupancy, and Individual VOT (2010 Dollars)

| Travel Type | Passenger Small Auto | Passenger Medium Auto | Passenger 4-Tire Truck | Single Unit 6-Tire Truck | Single Unit 3-4 Axle Truck | Combination 4-Axle Combination | Combination 5+ Axle Combination |
|---|---|---|---|---|---|---|---|
| **Business Travel** | | | | | | | |
| Value per Person* | $28.24 | $28.24 | $28.24 | $24.53 | $24.53 | $24.53 | $24.53 |
| Average Occupancy† | 1.15 | 1.15 | 1.12 | 1.05 | 1.00 | 1.12 | 1.12 |
| Vehicle‡ | $1.39 | $1.84 | $2.41 | $3.37 | $9.10 | $8.15 | $7.83 |
| Inventory§ | | | | | | $1.89 | $1.89 |
| **Personal Travel** | | | | | | | |
| Value per Person* | $14.12 | $14.12 | $14.12 | | | | |
| Average Occupancy† | 1.53 | 1.53 | 1.66 | | | | |
| Percent Personal** | 91% | 91% | 75% | | | | |
| **Average Value per Vehicle Hour** | **$22.70** | **$22.75** | **$26.09** | **$29.13** | **$33.63** | **$37.51** | **$37.19** |

* Individual VOTs for three categories are taken from Table 33 and applied to vehicle classes and travel purposes according to the assumed nature of the travel.

† Vehicle occupancies are taken from those used in the HERS model, which are adapted from the 1995 Nationwide Personal Transportation Survey (NPTS) and the 2009 National Household Travel Survey (NHTS). Passengers in the same vehicle are assumed to be used primarily as passenger vehicles.

‡ Vehicle depreciation is taken from the HERS model, and is based on a combination of vehicle wear from use and time-dependent obsolescence (HERS Technical Report, http://www.fhwa.dot.gov./infrastructure/asstmgmt/hersdoc.cfm).

§ Inventory costs are taken from the HERS model.

** Distribution between personal and business travel is taken from HERS, which uses NPTS and the 1992 Truck Inventory and Use Survey (TIUS). The estimate for personal share 4-tire truck travel was adjusted upward for HERS from 69 percent in the TIUS, based on the trend toward personal use of such vehicles.

**Table 33. Shares of Vehicle Miles Traveled by Roadway Type**

| Road Type | Passenger Small Auto | Passenger Medium Auto | Passenger 4-Tire Truck | Single Unit 6-Tire Truck | Single Unit 3-4 Axle Truck | Combination 4-Axle Combination | Combination 5+ Axle Combination |
|---|---|---|---|---|---|---|---|
| Urban Interstate/Expressway | 25% | 56% | 19% | 70% | 30% | 13% | 87% |
| Urban Arterial | 20% | 59% | 20% | 71% | 29% | 19% | 81% |
| Urban Other | 21% | 56% | 24% | 70% | 30% | 34% | 66% |
| Rural Interstate/Principal Arterial | 21% | 54% | 26% | 73% | 27% | 14% | 86% |
| Rural Other | 17% | 48% | 35% | 62% | 38% | 23% | 77% |
| **Total Rural and Urban** | **21%** | **55%** | **24%** | **69%** | **31%** | **20%** | **80%** |

Source: HERS/HPMS data

Using these shares as weights on the vehicle type hourly rates in Table 34 produces the hourly rates by road type shown in Table 34. The minor variations among the road types for the same vehicle type are due to the differences in the component types (e.g., four-tire trucks) with respect to occupancy and business travel share.

**Table 34. Average VOT per Vehicle Hour by Vehicle and Road Types (2010 Dollars)**

| Road Type | Passenger | Single Unit | Combination |
|---|---:|---:|---:|
| Urban Interstate/Expressway | $23.37 | $ 30.48 | $37.23 |
| Urban Arterial | $23.42 | $ 30.44 | $37.25 |
| Urban Other | $23.54 | $ 30.50 | $37.30 |
| Rural Interstate/Principal Arterial | $23.59 | $ 30.33 | $37.24 |
| Rural Other | $23.89 | $ 30.82 | $37.27 |
| **Total Rural and Urban** | **$23.54** | **$ 30.51** | **$37.26** |

Finally, if these rates are aggregated by weighting across vehicle types within the same road type, using the distribution from Table 16, the results are VOTs for each road type, as shown in Table 35. The global average is $24.34 per vehicle hour of delay, for all vehicles on all road types.

**Table 35. Average VOT by Road Type (2010 Dollars)**

| Road Type | Average VOT |
|---|---:|
| Urban Interstate/Expressway | $24.28 |
| Urban Arterial | $23.91 |
| Urban Other | $23.88 |
| Rural Interstate/Principal Arterial | $26.05 |
| Rural Other | $24.78 |
| **Total Rural and Urban** | **$24.34** |

## 3.9 FINAL DELAY COST ESTIMATES

Table 26 presents estimated vehicle hours of delay by severity and roadway type. The final, monetized estimates are presented in Table 37. These represent the culmination of the process outlined above. The estimated delay values are first collapsed by applying duration frequencies, then time of day frequencies are applied, and finally a value of time is applied.

Across roadway types, the estimated cost of delay increases with crash severity. Note that these estimates are the costs from delay only. Generally, fatal crashes have delay costs almost three times higher than injury only crashes. This result is driven by the finding that fatal crashes result in road closures of longer duration, as shown in Table 29. Interestingly, injury only crashes have delay costs only 20 percent higher than PDO crashes. The final column of Table 39 represents an estimated cost unconditional on severity. Urban Expressways have the highest costs of delay by at least a factor of 10. For a given severity, the costs of delay for Urban Arterials, Urban Others and Rural Expressways are similar. Rural Other roadways have relatively low costs of delay since traffic volumes are generally well below capacities.

**Table 36. Estimated Delay Vehicle Hours per Crash**

| Roadway Type | Fatal | Injury Only | PDO | Average for Road Type |
|---|---|---|---|---|
| Urban Interstate/Expressway | 6,729 | 2,522 | 2,144 | 2,265 |
| Urban Arterial | 483 | 137 | 109 | 118 |
| Urban Other | 291 | 108 | 91 | 97 |
| Rural Interstate/Principal Arterials | 464 | 159 | 134 | 142 |
| Rural Other | 99 | 34 | 28 | 30 |
| **Average for all Road Types** | **1,627** | **596** | **505** | **534** |

Results for delay per crash from a 2000 study by Zaloshnja et al. are given in Table 38. The distribution across severity levels was determined from police reports of the time spent by police at the scene, weighted by whether the crash involved an injury or fatality. This assumption means that the unit delays (per PDO, Injury or Fatal crash) are constrained in priority to be in the ratio of 40:130:285 for all road types.

The only data underlying these numbers are a secondhand average (5,057 hours) for 289 crashes on urban interstates in Minneapolis-St Paul reported by Lan and Hu (2000) in what is described in the report by Zaloshnja et al. as “personal communications.” The urban interstate results are then scaled to other roadway types on the basis of “traffic intensity,” or VMT per lane mile.

**Table 37. Estimated Delay Time Cost per Crash (2010 Dollars)**

| Roadway Type | Fatal | Injury Only | PDO | Average for Road type |
|---|---|---|---|---|
| Urban Interstate/Expressway | $163,792 | $61,395 | $52,175 | $55,121 |
| Urban Arterial | $11,760 | $3,328 | $2,649 | $2,876 |
| Urban Other | $7,086 | $2,628 | $2,222 | $2,351 |
| Rural Interstate/Principal Arterials | $11,303 | $3,860 | $3,258 | $3,458 |
| Rural Other | $2,421 | $821 | $684 | $729 |
| **Average for All Road Types** | **$39,602** | **$14,508** | **$12,280** | **$12,996** |

Thus the relatively wider dispersion across severity in the Zaloshnja et al., results is the consequence of an input assumption, and the decline in delay hours with functional class parallels the Volpe analysis in using VMT by roadway type as an input parameter.

### Table 38. Hours of Delay per Heavy Vehicle Crash by Roadway Class From Zaloshnja & Miller Report

| Road Class/Location | PDO | Injury | Fatal |
|---|---|---|---|
| **URBAN** | | | |
| Interstate | 2,260 | 7,344 | 21,749 |
| Other Freeway | 1,766 | 5,737 | 16,990 |
| Major Arterial | 949 | 3,082 | 9,127 |
| Minor Arterial | 594 | 1,929 | 5,711 |
| Collector | 31 | 102 | 301 |
| Local Street | 9 | 28 | 83 |
| **RURAL** | | | |
| Interstate | 814 | 2,646 | 7,835 |
| Major Arterial | 416 | 1,350 | 3,999 |
| Minor Arterial | 255 | 829 | 2,454 |
| Major Collector | 10 | 34 | 100 |
| Minor Collector | 4 | 14 | 42 |
| Local Street | 1 | 4 | 12 |

[This page intentionally left blank.]

# 4. EMISSIONS AND FUEL CONSUMPTION COSTS

As discussed in the previous section, road closures due to CMV crashes may result in increased vehicle delay. Other traffic on the roadway must slow down to pass a crash site that has resulted in a partial closure. If traffic volumes are high, the backup of traffic forming behind the road blockage may exhibit "stop and go" behavior as motorists jockey for position. In the case of full blockages, the traffic idles, not moving until the crash site is cleared. Some motorists will take longer detours around the crash site causing congestion on the surrounding road network. All of these crash impacts increase vehicle travel time. The extra time spent on the road also increase vehicle emissions and fuel consumption.

## 4.1 VEHICLE EMISSIONS MODELING

The emissions and fuel consumption analysis uses a novel approach in linking information from traffic simulation software to an emissions model. Although traffic simulation models like TSIS-CORSIM (University of Florida, McTrans Center, 2010) estimate the emissions and fuel consumption, the methodology employed within the model does not fully represent the effects traffic congestion has on motor vehicle emissions. The EPA's MOVES has the capability of incorporating vehicle specific drive cycles in estimating emission inventories (U.S. EPA, MOVES Software Design and Reference Manual, 2009).[17] MOVES replaced EPA's MOBILE6.2 as the required emissions model to be used for conducting analysis associated with transportation conformity or State Implementation Plans (U.S. EPA, 2003). There is currently a 2-year grace period before MOVES is fully transitioned to the required model.

MOBILE6.2 was originally designed as macro-scale emissions factor model and was not designed specifically for project level emissions analysis. MOVES can be used to conduct three levels of analysis: national, county, and project. The national- and county-level scales are used for conducting macro-scale emissions inventories. The project-level scale allows for the capability of linking traffic simulation model data to estimate emissions at a micro-scale level.

Descriptions of the emissions for which MOVES produces estimates are provided below. The descriptions are taken from various EPA Web pages.

**Carbon Dioxide ($CO_2$)** is a greenhouse gas emitted naturally through the carbon cycle and through human activities like fossil fuel combustion. Since the Industrial Revolution in the 1700's, human activities, such as burning oil, coal, and gas, have increased $CO_2$ concentrations in the atmosphere. The release of greenhouse gases and aerosols resulting from human activities are changing the amount of radiation coming into and leaving the atmosphere, likely contributing to changes in climate.

**Carbon Monoxide (CO)** is a colorless, odorless gas emitted from combustion processes. Nationally, the majority of CO emissions to ambient air come from mobile sources. CO can cause harmful health effects by reducing oxygen delivery to the body's organs (like the heart and brain) and tissues. At extremely high levels, CO can cause death.

---

[17] US EPA (2009).

**Hydro Carbon (HC) and Volatile Organic Compounds (VOC)** are a group of chemical compounds composed of carbon and hydrogen. When in gaseous form, hydrocarbons (HC) are called Volatile Organic Compounds (VOCs). They are generated via incomplete gasoline combustion or are petrochemical industry by-products. HC/VOCs include methane, gasoline and diesel vapors, benzene, formaldehyde, butadiene, and acetaldehyde. All HC/VOCs are carcinogenic to some extent, fatal at high concentrations, harmful to crops, and bio-accumulate within the food chain. All HC/VOCs contribute to smog, ground level ozone, and acid rain formation.

**Nitrous Oxides (NOx)** are a group of highly reactive gasses that include nitrogen dioxide ($NO_2$), nitrous acid, and nitric acid. $NO_2$ forms quickly from emissions from cars, trucks, and buses. In addition to contributing to the formation of ground-level ozone, and fine particle pollution, $NO_2$ is linked to a number of adverse effects to the respiratory system.

**Particulate Matter (PM)** is a complex mixture of extremely small particles and liquid droplets. Particle pollution is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles. The size of particles is directly linked to their potential to cause health problems; particles that are 10 microns in diameter or smaller generally pass through the throat and nose and enter the lungs. Once inhaled, these particles can affect the heart and lungs and cause serious health effects. EPA groups particulate pollution in two categories:

- Particulate matter smaller than 10 microns ($PM_{10}$), and larger than 2.5 microns in diameter; a size referred to as "inhalable coarse particles."
- Particulate matter smaller than 2.5 microns in diameter ($PM_{2.5}$), also known as "fine particle" emissions. These particles can be directly emitted from automobiles and react in the air.

**Sulfur Dioxide ($SO_2$)** is one of a group of highly reactive gases known as "oxides of sulfur." The largest source of $SO_2$ emissions occur from fossil fuel combustion and the pollutant is linked to a number of adverse effects on the respiratory system.

Previous research has attempted to assign a societal cost on the health and environmental effects of those emissions listed above. This research uses that previous work to calculate the costs of emissions from truck crash delay.

## 4.2 UNIT COSTS OF EMISSIONS CATEGORIES

The primary social cost of criteria pollutant emissions stems from their negative impact on human health. In general, estimates of the per-unit monetary cost of an emission largely depends on the emission's impact on mortality and morbidity rates. These rates are usually based on epidemiological studies, which track groups of individuals with different pollution exposures across long periods of time. By assigning a value to the loss of life or health that a unit of pollution causes, one can then place a social cost on the emissions themselves. Although determining the causal effects of pollution on health is challenging and controversial, a growing consensus of research has indicated that the health-related impacts of particulate pollution can be significant. Note that $CO_2$ is not considered a criteria pollutant and does not directly harm human health. The cost to society from $CO_2$ stems from its impact on climate change, and reflects the present discounted value of future losses of agriculture and biodiversity among others.

No single research paper provides all of the per-unit cost estimates for the emissions calculated by the MOVES model. Therefore, this report culls cost estimates from a variety of sources and uses USDOT, Office of Management and Budget, or EPA guidelines when available. The cost per short ton (2,000 pounds), in 2010 dollars, for each emissions category is listed in Table 39. Note that this report uses a single per-unit cost estimate for each of the types of pollution. These costs, however, should be interpreted as average costs—a unit increase in NOx emissions, for example, will have a greater health impact in a heavily populated area than in a sparsely populated rural area. Similarly, the emissions may have heterogeneous impacts based on weather and time of year.

**Table 39. Emissions Costs (2010 Dollars)**

| *Emission | Cost per Short Ton (2010 Dollars) | Source |
|---|---:|---|
| $CO_2$ | $21 | Interagency Working Group on Social Cost of Carbon (2010) |
| CO | $145 | McCubbin and Delucchi (1999) |
| NOx | $12,000 | Fann et al. (2009) |
| $PM_{10}$ | $46,094 | McCubbin and Delucchi (1999) |
| $PM_{2.5}$ | $270,000 | Pope et al. (2003) |
| $SO_2$ | $67,000 | Fann et al. (2009) |
| VOC | $2,800 | Fann et al. (2009) |

* A monetary cost for hydrocarbons was not identified for this study.

## 4.3 LINKING EMISSIONS TO VEHICLE DELAY

As mentioned previously, an important step in this project was developing a software program to translate the vehicle performance data (precise acceleration and deceleration data) from TSIS-CORSIM into vehicle specific power (VSP). VSP is a proxy variable for engine load that has been shown to be highly correlated with emissions (Zhai, Frey, & Rouphail, 2008) and produces more accurate emissions estimates than simply assuming constant velocities.

Unfortunately, the information on vehicle drive cycle (acceleration and deceleration profiles) from TSIS-CORSIM is not in a user-friendly format. In fact the data are intended to be used only in supporting animation of the traffic flows and is therefore produced in binary code that is read by TRAFVU (the animation software package of TSIS-CORSIM). An important research advance of this project is to develop a method to read the binary code and reformat it to be used in MOVES.

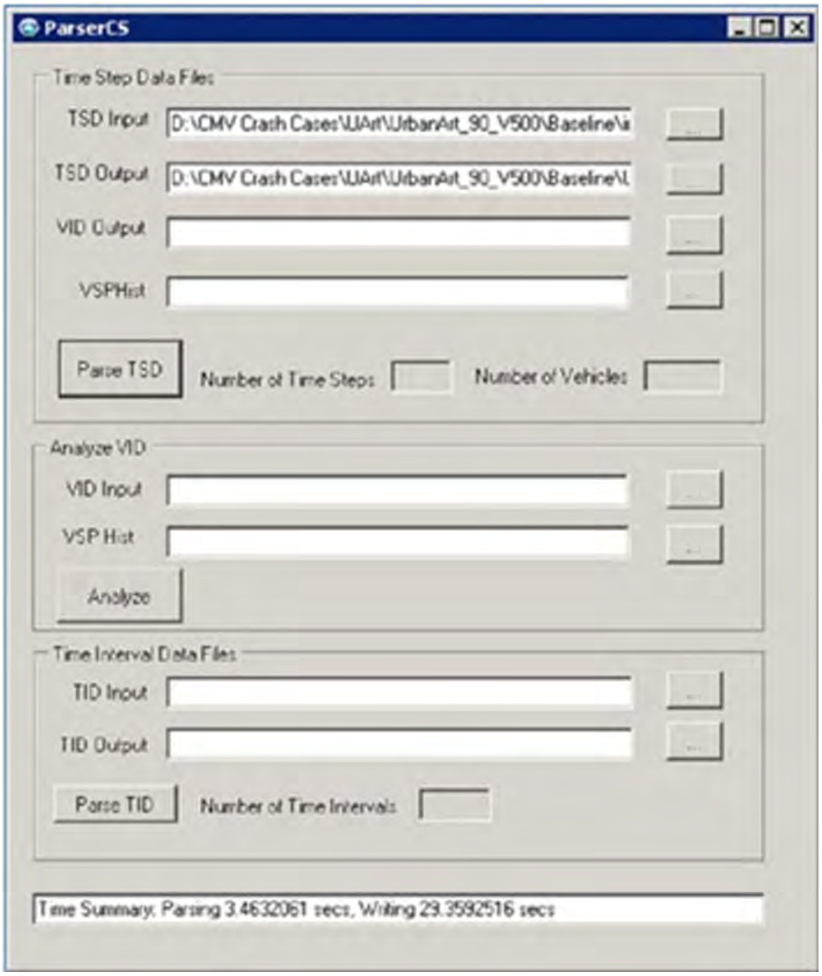
The Time Step Data (TSD) file is the binary file that contains all the position, velocity, and acceleration information for every vehicle included in the simulation. The vehicle type, location, velocity, and acceleration are the required parameters to build MOVES input file to calculate the scenario emissions and fuel consumption.

A three-step process was developed to link TSIS-CORSIM simulation data to a MOVES-ready input file.

1. TSD Binary Conversion.
2. Query Hourly Data.
3. Operating Mode Distribution Binning.

### 4.3.1 TSD Binary Conversion

In order to conduct the emissions and fuel consumption analysis a converter program needed to be created that translated the binary information within the TSD files being produced by TSIS-CORSIM for each scenario. The "parser" application was developed by Volpe to translate the binary information and organize the second-by-second information for every vehicle included in the simulation. Information such as the link identification, time step, vehicle type, velocity, and acceleration are organized into a comma-delimited file. Figure 40 displays the graphical user interface (GUI) for the "parser" application.



TSD Input: D:\CMV Crash Cases\UArt\UrbanArt_90_V500\Baseline\

TSD Output: D:\CMV Crash Cases\UArt\UrbanArt_90_V500\Baseline\

Time Summary: Parsing 3.4632061 secs, Writing 29.3592516 secs

Figure 40. Parser Application GUI

## 4.4 QUERY HOURLY DATA

After the “parser” application creates the comma-delimited file for each scenario, the data are separated into hourly components. Typically the TSIS-CORSIM simulation scenarios are executed at a 6-hour duration to ensure that the effects of the incident are dissipated. The MOVES project level scenario calculates the emissions and fuel consumption on an hourly basis; therefore the data need to be separated by each hourly component of the simulation. This is accomplished by importing the comma-delimited file into a Microsoft (MS) SQL[18] database. MS SQL is used because of its ability to process large amounts of data easily. For some scenarios, the TSD file was greater than 1 gigabyte in binary form. A file of that size equates to approximately 12 million rows of data. A MS SQL script separates the data into hourly components which are then used to determine the operating mode distribution bins for each vehicle type on each link. The concept of operating mode distribution bins is explained below.

## 4.5 VEHICLE SPECIFIC POWER

Specifying vehicle drive cycle information can be accomplished through either of two different features in MOVES: the Link Drive Schedule and the Operating Mode Distribution. The Link Drive Schedule allows the user to enter a vehicle specific drive cycle which is assigned to a roadway link. That drive cycle is then applied to all vehicles assigned on the link. The Operating Mode Distribution allows the user to assign the proportion of time vehicles on a link are operating within a specific operating mode bin. As a secondary step, MOVES translates the Link Drive Schedule into an operating mode distribution. This is accomplished by calculating the VSP. When a user utilizes the Link Drive Schedule within MOVES the VSP is calculated by the model and assigned to operating mode bins. When the user inputs an Operating Mode Distribution the user is responsible for calculating the VSP before the Operating Mode Distribution file is input into MOVES. Figure 410 shows the VSP calculation and variables (US EPA, MOVES Software Design and Reference Manual, 2009).

$$\frac{(VC_1) \times (T_A + VC_1) \times VC_1 \times (T_B + T_C V_1)}{M} + (VC_1 \times AC_1 + C_2 \sin \left( a \tan \left( \frac{grade}{100} \right) \right) VC$$

**Figure 41. Equation. Formula to Determine VSP, Which Predicts Emission Levels**

where $V$ = velocity
$A$ = acceleration
$C_1$ = conversion from miles per hour to meters per second (0.44704)
$C_2$ = gravitational constant in meters per second$^2$ (9.81)
$T_A$ = rolling term A
$T_B$ = rotating term B
$T_C$ = drag term C
$M$ = source mass
sin = sine trigonometric function
*a* tan = arctangent trigonometric function
*grade* = road grade in percentage

---

[18] Microsoft SQL Server 2008 Version R2 was used for this analysis.

For this analysis, developing operating mode distributions was chosen over developing link drive schedules. The link drive schedules only allow for one represented drive cycle per link per vehicle type. Since there are many vehicles traveling over an individual link for each hour being simulated, the drive cycles will vary depending on when the vehicle enters the link and experiences the traffic backup. By using the Operating Mode Distribution, the drive cycles for all vehicles are represented by the proportion of time all of the vehicles are in a specific operating mode distribution bin on an individual link.

## 4.6 OPERATING MODE DISTRIBUTION BINNING

To develop the operating mode distribution files for MOVES the hourly files separated in MS SQL were inputted back into the “parser” application to calculate the VSP for every vehicle on a second-by-second basis. To calculate the VSP, a mapping technique is needed to match the TSIS-CORSIM vehicle types to the MOVES vehicle types. Table 42 lists the vehicle type mapping and the required parameters for calculating the VSP.

**Table 40. TSIS-CORSIM to MOVES Vehicle Mapping and VSP Parameters**

| TSIS-CORSIM Vehicle Type | MOVES Source Type ID | MOVES Rolling Term A | MOVES Rotating Term B | MOVES Drag Term C | MOVES Source Mass | MOVES Fixed Mass Factor | MOVES Source Type Name |
|---|---|---|---|---|---|---|---|
| 1 | 21 | 0.156461 | 0.002002 | 0.000493 | 1.4788 | 1.4788 | Passenger Car |
| 2 | 21 | 0.156461 | 0.002002 | 0.000493 | 1.4788 | 1.4788 | Passenger Car |
| 3 | 52 | 0.561933 | 0 | 0.001603 | 7.64159 | 17.1 | Single Unit Short-Haul Truck |
| 4 | 52 | 0.561933 | 0 | 0.001603 | 7.64159 | 17.1 | Single Unit Short-Haul Truck |
| 5 | 52 | 0.561933 | 0 | 0.001603 | 7.64159 | 17.1 | Single Unit Short-Haul Truck |
| 6 | 62 | 2.08126 | 0 | 0.004188 | 31.4038 | 17.1 | Combination Long-Haul Truck |
| 8 | 21 | 0.156461 | 0.002002 | 0.000493 | 1.4788 | 1.4788 | Passenger Car |
| 9 | 21 | 0.156461 | 0.002002 | 0.000493 | 1.4788 | 1.4788 | Passenger Car |

Once the VSP is calculated the vehicle speed and the VSP value is required to be assigned into an operating mode bin. Table 41 lists an example of the operating mode distribution bins associated with this analysis.

## 4.7 MOVES MODELING

This analysis uses version MOVES2010a of EPA’s emissions model. Executing the MOVES model requires the user to provide project-level specific data. Meteorology data for the month of September, data for inspection and maintenance programs, and fuel formulation for Philadelphia County, PA, is used for this analysis. The vehicle age distribution is assumed to be 2010 and represents the national vehicle age distribution provided by the EPA. The vehicle fleet mixture was specific for each scenario being modeled as shown in Table 16.

For each roadway type, the 90-minute road closure duration is modeled for a baseline, partial closure, and full closure scenario. Also, 240-minute scenarios are modeled for full closure to account for the effects of vehicle diversion. All emissions are calculated as the net difference in emissions between the scenario and a baseline scenario run with no simulated crash.

**Table 41. Operating Mode Distribution Bins**

| ID | Operating Mode Name | VSP Lower | VSP Upper | Speed Lower | Speed Upper |
|---|---|---|---|---|---|
| 1 | Idling | - | - | -1 | 1 |
| 11 | Low Speed Coasting; VSP< 0; 1<=Speed<25 | - | 0 | 1 | 25 |
| 12 | Cruise/Acceleration; 0<=VSP< 3; 1<= Speed<25 | 0 | 3 | 1 | 25 |
| 13 | Cruise/Acceleration; 3<=VSP< 6; 1<=Speed<25 | 3 | 6 | 1 | 25 |
| 14 | Cruise/Acceleration; 6<=VSP< 9; 1<=Speed<25 | 6 | 9 | 1 | 25 |
| 15 | Cruise/Acceleration; 9<=VSP<12; 1<=Speed<25 | 9 | 12 | 1 | 25 |
| 16 | Cruise/Acceleration; 12<=VSP; 1<=Speed<25 | 12 | - | 1 | 25 |
| 21 | Moderate Speed Coasting; VSP< 0; 25<=Speed<50 | - | 0 | 25 | 50 |
| 22 | Cruise/Acceleration; 0<=VSP< 3; 25<=Speed<50 | 0 | 3 | 25 | 50 |
| 23 | Cruise/Acceleration; 3<=VSP< 6; 25<=Speed<50 | 3 | 6 | 25 | 50 |
| 24 | Cruise/Acceleration; 6<=VSP< 9; 25<=Speed<50 | 6 | 9 | 25 | 50 |
| 25 | Cruise/Acceleration; 9<=VSP<12; 25<=Speed<50 | 9 | 12 | 25 | 50 |
| 26 | Cruise/Acceleration; 12<=VSP; 25<=Speed<50 | 12 | - | 25 | 50 |
| 33 | Cruise/Acceleration; VSP< 6; 50<=Speed | - | 6 | 50 | - |
| 35 | Cruise/Acceleration; 6<=VSP<12; 50<=Speed | 6 | 12 | 50 | - |
| 36 | Cruise/Acceleration; 12 <= VSP; 50<=Speed | 12 | - | 50 | - |
| 27 | Cruise/Acceleration; 12<=VSP<18; 25<=Speed<50 | 12 | 18 | 25 | 50 |
| 28 | Cruise/Acceleration; 18<=VSP<24; 25<=Speed<50 | 18 | 24 | 25 | 50 |
| 29 | Cruise/Acceleration; 24<=VSP<30; 25<=Speed<50 | 24 | 30 | 25 | 50 |
| 30 | Cruise/Acceleration; 30<=VSP; 25<=Speed<50 | 30 | - | 25 | 50 |
| 37 | Cruise/Acceleration; 12<=VSP<18; 50<=Speed | 12 | 18 | 50 | - |
| 38 | Cruise/Acceleration; 18<=VSP<24; 50<=Speed | 18 | 24 | 50 | - |
| 39 | Cruise/Acceleration; 24<=VSP<30; 50<=Speed | 24 | 30 | 50 | - |
| 40 | Cruise/Acceleration; 30<=VSP; 50<=Speed | 30 | - | 50 | - |

## 4.8 SYNTHESIS

As noted earlier, only a finite number of simulations are modeled explicitly using MOVES. However the scenarios modeled explicitly are directly linked to the traffic simulations, and thus provide an estimate of total vehicle delay. This allows for an estimation of the excess emissions due to a CMV crash to be modeled as a function of delay, permitting the emissions to be scaled to any estimated delay. The results of the 90-minute and 240-minute MOVES simulations are shown in Table 42.

A separate function is estimated for each facility type and pollutant. The partial/full closure dimension is collapsed using frequency weights derived from the State-level data. The differing volumes and durations provide variation in the estimated delay amount for each of the scenarios. A simple linear function is then estimated based on these weighted delay and emissions amounts. The coefficients for these functions are reported in Table 43. These numbers are analogous to an emissions “rate” as they represent the relationship between vehicle hours of delay and the various emissions. Finally, these scaling factors are used to calculate expected emissions for an estimated delay value. These emissions can then be monetized to be included in a final crash cost.

**Table 42. Simulation Results (Net Short Tons of Emissions)**

| Simulation Number | Roadway Type | Net Delay | $CO_2$ | CO | NOx | $PM_{10}$ | $PM_{2.5}$ | $SO_2$ | Total HC | VOC |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | Urban Interstate/Expressway | 4,246.2 | 42.88116 | 0.29340 | 0.09346 | 0.00570 | 0.00548 | 0.00076 | 0.02623 | 0.02565 |
| 4 | Urban Interstate/Expressway | 11,410.9 | 30.65246 | 0.21389 | 0.05069 | 0.00494 | 0.00478 | 0.00056 | 0.02598 | 0.02565 |
| 6 | Urban Interstate/Expressway | 2,963.6 | 23.29352 | 0.16583 | 0.06061 | 0.00315 | 0.00303 | 0.00040 | 0.01104 | 0.01079 |
| 10 | Urban Interstate/Expressway | 2,416.3 | 19.98111 | 0.13436 | 0.04290 | 0.00260 | 0.00250 | 0.00035 | 0.01222 | 0.01196 |
| 11 | Urban Interstate/Expressway | 3,382.5 | 9.37876 | 0.07810 | 0.00536 | 0.00180 | 0.00174 | 0.00018 | 0.01054 | 0.01045 |
| 13 | Urban Interstate/Expressway | 1,023.5 | 7.31047 | 0.05465 | 0.01888 | 0.00100 | 0.00097 | 0.00013 | 0.00349 | 0.00341 |
| 17 | Urban Interstate/Expressway | 827.7 | 2.81731 | 0.01691 | 0.00538 | 0.00034 | 0.00032 | 0.00005 | 0.00186 | 0.00183 |
| 18 | Urban Interstate/Expressway | 766.1 | 3.75873 | 0.02962 | 0.00154 | 0.00068 | 0.00066 | 0.00008 | 0.00416 | 0.00414 |
| 20 | Urban Interstate/Expressway | 7 | 0.04773 | 0.00160 | -0.00002 | 0.00001 | 0.00001 | 0.00000 | 0.00003 | 0.00003 |
| 24 | Urban Arterial | 458.9 | 8.13007 | 0.06097 | 0.01610 | 0.00085 | 0.00081 | 0.00014 | 0.00373 | 0.00362 |
| 25 | Urban Arterial | 914.0 | 10.22945 | 0.06204 | 0.01728 | 0.00078 | 0.00074 | 0.00017 | 0.00438 | 0.00426 |
| 27 | Urban Arterial | 114.2 | -0.21373 | -0.00191 | -0.00023 | -0.00001 | -0.00001 | 0.00000 | 0.00000 | -0.00006 |
| 31 | Urban Arterial | 195.4 | 3.41353 | 0.02233 | 0.00660 | 0.00035 | 0.00034 | 0.00006 | 0.00165 | 0.00161 |
| 32 | Urban Arterial | 364.3 | 4.44467 | 0.02957 | 0.00956 | 0.00045 | 0.00043 | 0.00007 | 0.00176 | 0.00171 |
| 34 | Urban Arterial | 32.6 | 0.16361 | 0.00150 | 0.00029 | 0.00001 | 0.00001 | 0.00000 | 0.00005 | 0.00005 |
| 38 | Urban Other | 369.3 | 1.96281 | 0.01194 | 0.00357 | 0.00014 | 0.00013 | 0.00004 | 0.00069 | 0.00068 |
| 39 | Urban Other | 814.0 | 4.14793 | 0.02549 | 0.00765 | 0.00029 | 0.00028 | 0.00007 | 0.00146 | 0.00142 |
| 41 | Urban Other | 8.5 | 0.06165 | 0.00043 | 0.00008 | 0.00000 | 0.00000 | 0.00000 | 0.00003 | 0.00003 |
| 45 | Urban Other | 253.1 | 0.97964 | 0.00590 | 0.00177 | 0.00007 | 0.00006 | 0.00002 | 0.00034 | 0.00034 |
| 46 | Urban Other | 590.6 | 2.07174 | 0.01267 | 0.00381 | 0.00014 | 0.00014 | 0.00004 | 0.00073 | 0.00071 |
| 48 | Urban Other | 5.3 | 0.02843 | 0.00015 | 0.00004 | 0.00000 | 0.00000 | 0.00000 | 0.00001 | 0.00001 |
| 52 | Rural Interstate/Principal Arterials | 919.7 | 5.97071 | 0.03684 | 0.02543 | 0.00143 | 0.00138 | 0.00009 | 0.00351 | 0.00347 |
| 53 | Rural Interstate/Principal Arterials | 768.0 | 6.62569 | 0.04379 | 0.02451 | 0.00132 | 0.00127 | 0.00010 | 0.00267 | 0.00260 |
| 55 | Rural Interstate/Principal Arterials | 27.2 | 0.03698 | 0.00150 | 0.00002 | 0.00002 | 0.00002 | 0.00000 | 0.00003 | 0.00003 |
| 59 | Rural Interstate/Principal Arterials | 257.4 | 1.78392 | 0.01266 | 0.00749 | 0.00043 | 0.00042 | 0.00003 | 0.00099 | 0.00097 |
| 60 | Rural Interstate/Principal Arterials | 360.1 | 3.08042 | 0.02038 | 0.01044 | 0.00055 | 0.00053 | 0.00005 | 0.00109 | 0.00106 |

| Simulation Number | Roadway Type | Net Delay | $CO_2$ | CO | NOx | $PM_{10}$ | $PM_{2.5}$ | $SO_2$ | Total HC | VOC |
|---|---|---|---|---|---|---|---|---|---|---|
| 62 | Rural Interstate/Principal Arterials | 0.2 | 0.00391 | 0.00045 | -0.00004 | 0.00000 | 0.00000 | 0.00000 | 0.00001 | 0.00001 |
| 66 | Rural Other | 101.0 | 0.55160 | 0.00387 | 0.00181 | 0.00011 | 0.00010 | 0.00001 | 0.00021 | 0.00021 |
| 67 | Rural Other | 273.7 | 3.37028 | 0.02042 | 0.01082 | 0.00055 | 0.00053 | 0.00005 | 0.00131 | 0.00129 |
| 69 | Rural Other | 9.3 | 0.02948 | 0.00004 | -0.00004 | 0.00001 | 0.00001 | 0.00000 | 0.00005 | 0.00005 |
| 73 | Rural Other | 45.1 | 0.16153 | 0.00097 | 0.00058 | 0.00003 | 0.00003 | 0.00000 | 0.00006 | 0.00006 |
| 74 | Rural Other | 104.4 | 1.10904 | 0.00666 | 0.00361 | 0.00018 | 0.00017 | 0.00002 | 0.00043 | 0.00042 |
| 76 | Rural Other | 3.0 | 0.00578 | -0.00007 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00002 | 0.00002 |

**Table 43. Emissions Coefficients—Short Tons or MMBTU per Vehicle Hour of Delay**

| Roadway Type | $CO_2$ | CO | NOx | Fuel | $PM_{10}$ | $PM_{2.5}$ | $SO_2$ | Total HC | VOC |
|---|---|---|---|---|---|---|---|---|---|
| Urban Interstate/Expressway | 4.76E-03 | 3.35E-05 | 8.64E-06 | 5.16E-02 | 7.31E-07 | 7.06E-07 | 8.56E-08 | 3.65E-06 | 3.60E-06 |
| Urban Arterial | 1.71E-02 | 1.08E-04 | 3.05E-05 | 1.96E-01 | 1.42E-06 | 1.35E-06 | 2.88E-07 | 7.35E-06 | 7.13E-06 |
| Urban Other | 8.78E-03 | 5.39E-05 | 1.61E-05 | 9.85E-02 | 6.15E-07 | 5.87E-07 | 1.61E-07 | 3.10E-06 | 3.02E-06 |
| Rural Interstate/Principal Arterials | 1.15E-02 | 7.56E-05 | 4.40E-05 | 1.37E-01 | 2.41E-06 | 2.33E-06 | 1.73E-07 | 5.22E-06 | 5.12E-06 |
| Rural Other | 2.12E-02 | 1.29E-04 | 6.82E-05 | 2.69E-01 | 3.51E-06 | 3.37E-06 | 3.18E-07 | 8.30E-06 | 8.13E-06 |

Estimated values for the various emissions are presented in Table 46 through Table 49. These tables present the estimated short tons of emissions by facility type. They are estimated by applying the linear factors in Table 43 to the estimated delay values by severity and facility type. Table 44 presents the estimated short tons unconditional on severity. Table 45, Table 46, and Table 47 present short tons of emissions by facility type for Fatal, Injury Only, and PDO crashes. These are estimated in a similar manner of applying the linear scaling factors to the estimated delay for each roadway type/severity combination. These values follow a similar pattern to that seen in the delay estimates, as would be expected. Fatal crashes tend to produce the largest amount of excess emissions while PDO crashes produce the least. The overall average emissions are close to the PDO amount due to the overwhelming frequency of PDO crashes when compared with other severities.

## Table 44. Estimated Net Emissions by Roadway Type (Short Tons)

| Roadway Type | $CO_2$ | CO | NOx | $PM_{10}$ | $PM_{2.5}$ | $SO_2$ | Total HC | VOC |
|---|---|---|---|---|---|---|---|---|
| Urban Interstate/Expressway | 10.77391 | 0.07593 | 0.01957 | 0.00166 | 0.00160 | 0.00019 | 0.00827 | 0.00815 |
| Urban Arterial | 2.01570 | 0.01274 | 0.00360 | 0.00017 | 0.00016 | 0.00003 | 0.00087 | 0.00084 |
| Urban Other | 0.84827 | 0.00520 | 0.00156 | 0.00006 | 0.00006 | 0.00002 | 0.00030 | 0.00029 |
| Rural Interstate/Principal Arterials | 1.63494 | 0.01074 | 0.00625 | 0.00034 | 0.00033 | 0.00002 | 0.00074 | 0.00073 |
| Rural Other | 0.63542 | 0.00385 | 0.00204 | 0.00011 | 0.00001 | 0.00001 | 0.00025 | 0.00024 |
| **Average for All Roadway Types** | **3.21700** | **0.02192** | **0.00661** | **0.00047** | **0.00045** | **0.00006** | **0.00210** | **0.00207** |

## Table 45. Estimated Net Emissions by Roadway Type (Short Tons)—Fatal Crashes

| Roadway Type | $CO_2$ | CO | NOx | $PM_{10}$ | $PM_{2.5}$ | $SO_2$ | Total HC | VOC |
|---|---|---|---|---|---|---|---|---|
| Urban Interstate/Expressway | 32.01443 | 0.22563 | 0.05816 | 0.00492 | 0.00475 | 0.00058 | 0.02456 | 0.02421 |
| Urban Arterial | 8.24277 | 0.05208 | 0.01474 | 0.00069 | 0.00065 | 0.00014 | 0.00355 | 0.00344 |
| Urban Other | 2.55629 | 0.01568 | 0.00470 | 0.00018 | 0.00017 | 0.00005 | 0.00090 | 0.00088 |
| Rural Interstate/Principal Arterials | 5.34325 | 0.03512 | 0.02044 | 0.00112 | 0.00108 | 0.00008 | 0.00242 | 0.00238 |
| Rural Other | 2.11074 | 0.01280 | 0.00678 | 0.00035 | 0.00033 | 0.00003 | 0.00083 | 0.00081 |
| **Average for All Roadway Types** | **10.20434** | **0.06922** | **0.02102** | **0.00145** | **0.00140** | **0.00018** | **0.00652** | **0.00641** |

### Table 46. Estimated Net Emissions by Roadway Type (Short Tons)—Injury Only Crashes

| Roadway Type | $CO_2$ | CO | NOx | $PM_{10}$ | $PM_{2.5}$ | $SO_2$ | Total HC | VOC |
|---|---|---|---|---|---|---|---|---|
| Urban Interstate/Expressway | 12.00008 | 0.08458 | 0.0218 | 0.00184 | 0.00178 | 0.00022 | 0.00921 | 0.00907 |
| Urban Arterial | 2.33296 | 0.01474 | 0.00417 | 0.00019 | 0.00018 | 0.00004 | 0.00101 | 0.00097 |
| Urban Other | 0.94816 | 0.00582 | 0.00174 | 0.00007 | 0.00006 | 0.00002 | 0.00033 | 0.00033 |
| Rural Interstate/Principal Arterials | 1.8246 | 0.01199 | 0.00698 | 0.00038 | 0.00037 | 0.00003 | 0.00083 | 0.00081 |
| Rural Other | 0.71551 | 0.00434 | 0.0023 | 0.00012 | 0.00011 | 0.00001 | 0.00028 | 0.00027 |
| **Average for All Road Types** | **3.60564** | **0.02456** | **0.0074** | **0.00052** | **0.0005** | **0.00006** | **0.00235** | **0.00231** |

### Table 47. Estimated Net Emissions by Roadway Type (Short Tons)—PDO Crashes

| Roadway Type | $CO_2$ | CO | NOx | $PM_{10}$ | $PM_{2.5}$ | $SO_2$ | Total HC | VOC |
|---|---|---|---|---|---|---|---|---|
| Urban Interstate/Expressway | 10.19796 | 0.07187 | 0.01853 | 0.00157 | 0.00151 | 0.00018 | 0.00782 | 0.00771 |
| Urban Arterial | 1.85693 | 0.01173 | 0.00332 | 0.00015 | 0.00015 | 0.00003 | 0.0008 | 0.00078 |
| Urban Other | 0.80165 | 0.00492 | 0.00147 | 0.00006 | 0.00005 | 0.00001 | 0.00028 | 0.00028 |
| Rural Interstate/Principal Arterials | 1.54022 | 0.01012 | 0.00589 | 0.00032 | 0.00031 | 0.00002 | 0.0007 | 0.00069 |
| Rural Other | 0.59663 | 0.00362 | 0.00192 | 0.0001 | 0.00009 | 0.00001 | 0.00023 | 0.00023 |
| **Average for All Road Types** | **3.03105** | **0.02066** | **0.00622** | **0.00044** | **0.00042** | **0.00005** | **0.00198** | **0.00195** |

Table 48 presents an estimated total cost of emissions by roadway type and severity. These are calculated using the emissions estimates given in the previous tables and the prices outlined in Table 39. Note that total HC is implicitly valued at zero. These values are small by comparison with the delay estimates. The Rural Other estimates are the largest relative to the delay estimates, yet represent about 10 percent of the dollar cost due to delay. Urban Interstate/Expressway crashes are the smallest, with the cost of emissions being less than 2 percent of the cost of delay.

**Table 48. Estimated Cost of Emissions per Crash (2010 Dollars)**

| Roadway Type | Fatal | Injury Only | PDO | Average for Road Type |
|---|---|---|---|---|
| Urban Interstate/Expressway | $3,019 | $1,132 | $962 | $1,016 |
| Urban Arterial | $584 | $165 | $132 | $143 |
| Urban Other | $172 | $64 | $54 | $57 |
| Rural Interstate/Principal Arterial | $718 | $245 | $207 | $220 |
| Rural Other | $238 | $81 | $67 | $72 |
| **Average for All Roadway Types** | **$951** | **$338** | **$285** | **$302** |

## 4.9 EXCESS FUEL CONSUMPTION

The MOVES model provided fuel consumption estimates for each simulation in millions British Thermal Units (MMBtu). However, MOVES outputs the fuel consumption estimates in aggregate and did provide separation of diesel versus gasoline fuel consumed for each simulation. The breakdown of diesel to gasoline fuel consumption was obtained by reviewing the ratios of fuel consumption output from TSIS-CORSIM for the baseline simulation for each roadway type. TSIS-CORSIM provides fuel consumed by each of the nine vehicle types which are listed in Table 40. The diesel and gasoline ratios for each facility type are listed in Table 49.

**Table 49. Diesel and Gasoline Consumption Percentages**

| Roadway Type | Diesel Factor | Gas Factor |
|---|---|---|
| Urban Interstate/Expressway | 0.44 | 0.56 |
| Urban Arterial | 0.50 | 0.50 |
| Urban Other | 0.33 | 0.67 |
| Rural Interstate/Principal Arterial | 0.32 | 0.68 |
| Rural Other | 0.60 | 0.40 |

These gasoline and diesel percentages allow the fuel burn to be separated into the two distinct fuel types. As gasoline and diesel contain different energy content per gallon, different conversion rates are applied to calculate gallons of fuel burn. Additionally, different costs per gallon can be applied for a more accurate final cost calculation. Table 50 provides the different energy content and prices used for gasoline and diesel. The prices are net of State and Federal taxes. State and Federal tax information was taken from EIA Petroleum Marketing Monthly (April 2011) while the prices represent 2010 average annual prices as reported by EIA.

**Table 50. Price and Energy Content for Gasoline and Diesel**

| | Diesel | Gasoline |
|---|---:|---:|
| Energy Content (BTU/gal) | 138,700 | 125,000 |
| Price (2010 Dollars) | $2.517 | $2.430 |

Source: EIA Petroleum Marketing Monthly (April 2011) and Davis, et al., DOE Transportation Energy Data Book (2010)

Table 51 presents the excess fuel burn by severity and roadway type in combined gasoline and diesel gallons. These values follow similar patterns to the delay and emissions numbers. Fatal accidents produce the most excess fuel burn while PDO crashes produce the least.

**Table 51. Estimates of Excess Fuel Burn by Roadway Type and Severity (Gallons)**

| Roadway Type | Fatal | Injury Only | PDO | Average for Road Type |
|---|---:|---:|---:|---:|
| Urban Interstate/Expressway | 2,655.95 | 995.54 | 846.03 | 893.81 |
| Urban Arterial | 733.93 | 207.72 | 165.34 | 179.48 |
| Urban Other | 222.13 | 82.39 | 69.66 | 73.71 |
| Rural Interstate/Principal Arterial | 483.72 | 165.18 | 139.43 | 148.01 |
| Rural Other | 201.19 | 68.2 | 56.87 | 60.57 |
| **Average for All Roadway Types** | **872.03** | **307.22** | **258.12** | **274.02** |

Table 52 presents a monetized version of the fuel burn estimates. While these costs are higher than those of the excess emissions, these costs are still relatively small when compared to the cost of delay. Again, Rural Other is the highest where the cost of excess fuel burn is approximately 20 percent of the cost of delay on that roadway type. The cost of excess fuel burn on Urban Interstate/Expressway is less than 5 percent of the delay cost. Thus, while not negligible, excess fuel burn and emissions are comparatively small costs.

**Table 52. Estimates of Cost of Excess Fuel Burn per Crash (2010 Dollars)**

| Roadway Type | Fatal | Injury Only | PDO | Average for Road Type |
|---|---:|---:|---:|---:|
| Urban Interstate/Expressway | $6,544 | $2,453 | $2,084 | $2,202 |
| Urban Arterial | $1,801 | $510 | $406 | $440 |
| Urban Other | $545 | $202 | $171 | $181 |
| Rural Interstate/Principal Arterial | $1,194 | $408 | $344 | $365 |
| Rural Other | $499 | $169 | $141 | $150 |
| **Average for All Roadway Types** | **$2,147** | **$757** | **$636** | **$675** |

## 4.10 FUEL TANK LEAKS

Fuel leaks present another source of costs associated with a truck crash. Crashes with fuel tank leaks are not explicitly excluded, thus the average delay numbers represent any delay due to fuel leakage. That said, there are three things that fuel spills contribute that are not already accounted for: additional emissions from spilled fuel, the dollar value of the spilled fuel, and the costs associated with the fuel cleanup. The latter is outside the scope of this report, but estimates of cleanup costs are provided in previous studies by Zaloshnja and Miller. Any additional delay caused by the requisite cleanup would be accounted for by the increase in road closure time and is already included in the overall averages.

To estimate the additional emissions and dollar value of spilled fuel several pieces of information are required. First, an estimate of the frequency of these events is required. Second, estimates of the gallons spilled in each crash (or an average number of gallons leaked) are needed. Third, a dollar-per-gallon value is required to calculate the cost of spilled fuel. This price information is readily available and contained in this report. Lastly, estimates of the emissions per gallon of fuel are required. Those four pieces of data would allow an average amount of emissions from fuel spilled and an average dollar value of spilled fuel per crash to be calculated. GES and FARS do not contain information on the presence of fuel spills for a given crash, making the determination of the frequency of these events difficult. A 1985 report from the University of Michigan, however, provides estimates of fuel leakages rates.[19] These estimates are provided in Table 53. The age of these data likely renders them an approximation at best. Additionally, there is no information on how the frequency of leaks varies according to injury severity.

**Table 53. Fire and Fuel Leakage by Vehicle Type, Michigan 1982**

| Vehicle Type | Fuel Leak | Fire | No Leak or Fire | Total | Fuel Leak Percent |
|---|---:|---:|---:|---:|---:|
| Passenger Car | 3,017 | 877 | 376,336 | 380,230 | 0.80% |
| Straight Truck | 831 | 152 | 67,474 | 68,457 | 1.20% |
| Tractor-Trailer | 326 | 36 | 4,641 | 5,003 | 6.50% |
| **All Vehicle Types** | **4,174** | **1,065** | **448,451** | **453,690** | **0.90%** |

As the estimates in this study are not differentiated by truck type, an estimate of leakage rates independent of truck type must be developed. FARS and GES provide information regarding truck type. Table 54 provides an estimated breakdown that is in line with the information presented in Table 53. Note that this breakdown includes only tractor-trailer and straight truck vehicles; no information is provided about fuel leakage rates for other vehicles types (i.e., buses). The distribution presented in Table 54 assumes that unknown or other vehicle types are distributed according to the proportionally between straight and trailer vehicles. By taking the weighted average of the rates in Table 53, using the weights indicated in Table 54, a fuel leakage rate can be estimated that is independent of vehicle type. This process results in an estimated 4.02 percent of trucks involved in crashes having fuel leaks.

Another factor to consider in determining overall fuel leakage frequency is the prevalence of single- or multiple-vehicle crashes. Crashes involving multiple trucks, for instance, have a higher rate of fuel leakage merely by including additional vehicles. FARS and GES contain information on the number of vehicles involved in a crash (both parked and moving vehicles). This can be used to determine the average number of vehicles involved in a multi-vehicle crash. Table 55 provides the distribution of vehicles involved in a CMV crash from GES and FARs.

---

[19] O'Day, James; Robin Ruthazer; Tom Gonzales. "An In-Depth Study of Truck Fire Accident Data." The University of Michigan Transportation Research Institute. April 1985.

Additionally, the table contains information on the average number of vehicles involved in multi-vehicle crashes.

**Table 54. Vehicle Type Distribution**

| Vehicle Type | Percent of Vehicles |
|---|---|
| Straight Truck | 53% |
| Tractor-Trailer | 47% |

**Table 55. Number of Vehicles Involved in CMV Crashes**

| Vehicles Involved | Percent or Vehicles |
|---|---|
| 1 Vehicle Involved | 14% |
| 2 Vehicles Involved | 79% |
| 3+ Vehicles Involved | 7% |
| Average Vehicles Involved | 2.1 |

While the crashes examined for this report must include at least one CMV, multi-vehicle crashes may contain only one truck and multiple passenger cars. Table 53 in the Large Truck and Bus Crash Facts 2008 compilation published by FMCSA provides some information on the prevalence of truck crashes involving other motor vehicles and non-motor vehicles. Table 56 provides an estimated distribution of truck crashes involving passenger vehicles. Given the average number of vehicles involved in a CMV crash, it is safe to assume that the average crash involving a passenger car involves only one truck. Therefore, after removing single-truck crashes (14 percent) and CMV crashes involving passenger cars (58 percent), the remaining crashes (28 percent) will be assumed to involve multiple trucks.

Multiplying the single-truck leak rate by the average number of vehicles involved in a crash (i.e., assuming that fuel leakage is an independent event for each truck) gives an estimate of the leakage rate for multi-truck crashes (approximately 8.44 percent). Combining the distribution of crashes provided in Table 56 with the estimates of leakage rates for single- and multi-truck crashes results in an overall average leakage rate, unconditional of any other information. Table 57 reports these estimates of single truck, multi-truck, and overall average fuel leakage rates.

**Table 56. Truck Crash Frequency by Vehicles Involved**

| Vehicles Involved | Percent |
|---|---:|
| Single Truck | 14% |
| Single Truck With Passenger Car | 58% |
| Multi-Truck | 28% |

Table 57. Fuel Leakage Rate by Crash Type

| Crash Type | Fuel Leakage Rate |
|---|---:|
| Single Truck | 4.02% |
| Multi-Truck | 8.44% |
| Average Crash | 5.27% |

The previous discussion revolves around developing an estimate of the frequency of truck fuel leaks. As described above, the second piece of information required to develop an average cost of fuel leakage is an estimate of gallons leaked per crash. This information is not contained in FARS or GES and a brief search turned up only anecdotal information. Thus, the estimate of gallons spilled per crash is kept separate from the estimate of the frequency of fuel leakage. This allows the estimates to be updated as better information becomes available on either measure. Table 58 presents assumed values of gallons leaked. These are based on maximum fuel tank capacity for each vehicle classification and are approximately "half full."

Table 58. Leaked Gallons per Crash Assumptions

| Vehicle Type (Fuel Type) | Gallons Leaked per Crash |
|---|---:|
| Truck (Diesel) | 150 |
| Passenger Car (Gasoline) | 10 |

Finally, the estimates of frequency and gallons per crash can be combined into a fuel spill amount for the average crash. Note that this is regardless of truck type, roadway type, and crash severity. Thus, these estimates are best compared to the grand averages presented earlier in the report. Table 59 presents gallon estimates for diesel and gasoline (from passenger cars) spilled for the average crash. Additionally, cost estimates are provided using the prices listed in Table 50. Emissions values are not provided because estimates of excess emissions by gallon are not available. Note that the additional cost is quite small compared to the excess fuel burn for an average crash. Thus, while a fuel spill may contribute greatly to the lost fuel for a given event, on average fuel spills contribute little to the total cost of an average crash.

Table 59. Average Gallons Spilled and Value of Spilled Fuel

| Fuel Type | Average Gallons Spilled | Value of Spilled Gallons |
|---|---:|---:|
| Diesel | 7.91 | $19.90 |
| Gasoline | 0.05 | $0.11 |

# 5. CRASHES INVOLVING HAZARDOUS MATERIALS

A small share of CMV crashes involve some type of HM, such as gasoline, nitrogen fertilizer, or fireworks. The bulk of this report uses data sources that cover all CMV crashes, which will necessarily include the crashes involving HMs. Hence, the estimates of average costs of CMV crashes using these data sources include the costs of HM crashes in proportion to the prevalence of HM crashes in the universe of all CMV crashes.

For some purposes, however, it may be desirable to have crash costs specifically for HM crashes. This section uses data pertaining specifically to HM incidents to construct estimates of certain costs for this type of crash.

## 5.1 HM

For the purposes of this report, HM crashes are those where the cargo of the CMV was placarded HM. Although gasoline used to fuel a CMV can be considered a HM, CMV crashes that include release of gasoline from a fuel tank are not considered in this section.

## 5.2 ESTIMATING HM COSTS

The goal was to calculate costs across a variety of vehicle configuration, HM, and cost categories. In order to generate estimated cross-tabulations for these breakdowns, two main data sources are used. These sources facilitate estimating costs specific to vehicle configuration, type of HM, and break down the cost components into separate categories. The primary data source for estimating HM crash costs is the PHMSA HMIS, which provided cost and material type for a large number of HM crashes. Although this dataset is rich with crash-specific detail, it lacks information on truck configurations. Fortunately, MCMIS contains such data. There are sufficient overlapping characteristics in both datasets to allow a portion of the HM crash records to be matched between them, which provide a more complete description of HM crashes.

## 5.3 CONSEQUENCES OF HM CRASHES

Clean-up time can, if the road is closed, significantly affect the delay created by a crash. Hence, congestion and emission costs should be calculated separately for crashes that involve HMs. The strategy for estimating costs of crashes in which HMs are involved is to assume initially that HM involvement introduces some additional costs but does not change the basic delay and emissions costs of the same crash without HM involvement. For example, if HM involvement increases total incident duration, then the initial delay estimate will be scaled up appropriately.

Additional costs due to HM involvement depend upon how procedures for handling the incident are altered in the face of HM presence. These procedures follow relevant law and are implemented primarily by state police. Volpe staff informally queried State highway patrol officials in Massachusetts and learned that when there is a crash with HMs, officers refer to the Emergency Response Guide—commonly referred to as the “3-minute guide”—to determine the appropriate response. The guide describes how to protect the public from each specific substance, but does not specify traffic procedures. The highway patrol decides how to deal with traffic on a case-by-case basis. For many HM crashes this simply involves applying a neutralizing solution to the spill and closing off the single lane of traffic that is affected. It is rare for the highway patrol to close traffic in the opposing direction. Typical HM spills are estimated to require double the time it takes to clear an accident. The distribution of HM delay is skewed to the right with the rare hazardous spill increasing incident duration dramatically.

The most common methods used by the highway patrol to notify the public of a traffic delay are variable message signs above the road and an announcement to the media, which is then transmitted to the public over the radio or television. Truck drivers learn of traffic delays much sooner over CB radio.

The presence of a HM is not expected to affect the likelihood of a crash, but it can have a large impact on the duration of an incident and the amount and extent of damage. Figure 42, using crash data from Pennsylvania, compares the distribution of crash durations between HM and non-HM crashes. Note that HM crashes are more likely to result in long duration closures.

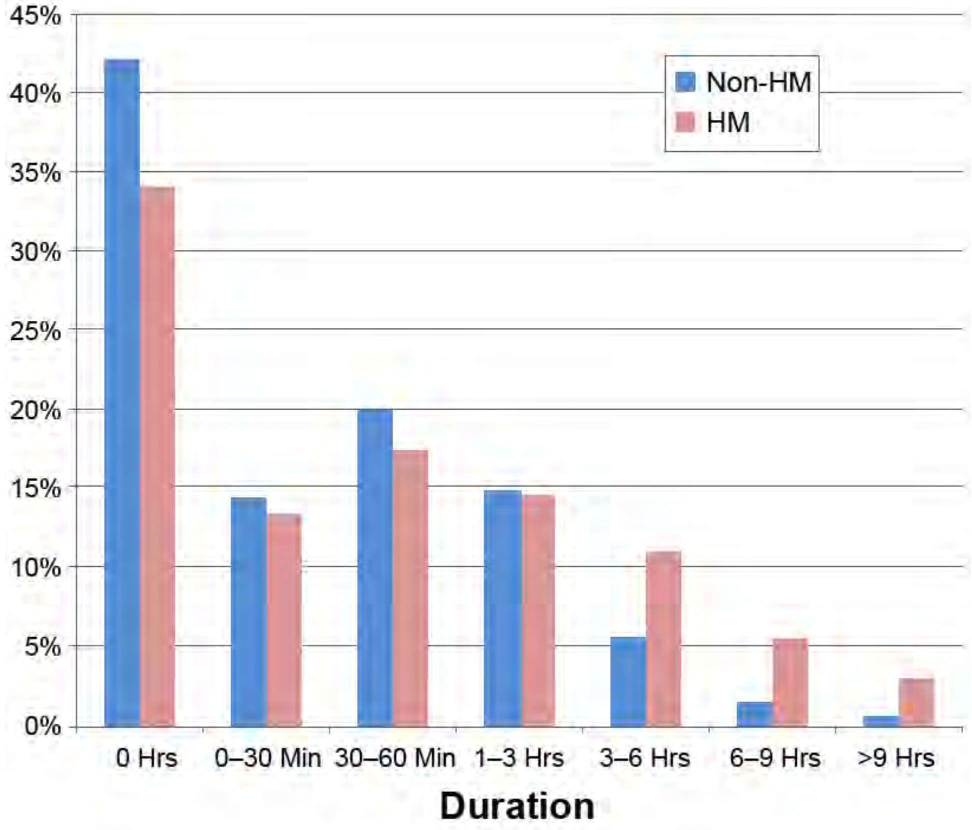


**Figure 42. Histogram of Duration by Presence of HM**

## 5.4 OVERVIEW OF DATASETS

### 5.4.1 Hazardous Materials Incident System

The HMIS includes the following information regarding HM crashes:[20]

- Dollar value of damage by cost category:
    - Damage to the materials being transported.
    - Damage to the carrier's vehicle.
    - Damage to other vehicles and property.
    - Emergency response costs.
    - Cleanup costs.
- HM being transported: toxic, explosive, biohazard, etc.
- Crash severity (number of injuries and fatalities).
- County in which the crash occurred.
- Day on which the crash occurred.

Although the HMIS reports crash cost data for individual crashes, it is important to note that the data is almost entirely self-reported by carriers. Following a crash, a carrier has a 30-day window to complete a HMIS report, which is sent to PHMSA. The carrier is required to estimate the level of damages in each of the categories listed below the first bullet above. The self-reported data is the best available source of information regarding costs, but it is far from perfect. The main problem is that the carrier may not know the true cost of external damages it may have caused. For example, the material and carrier damage costs should be precise (because of the carrier's intimacy with its trucking equipment), but it is less likely that the carrier would be able to accurately estimate elements such as the emergency response costs. So the results from the emergency response and cleanup categories should be interpreted cautiously and likely represent a lower bound for an estimate of the true costs.

A second problem with the HMIS data involves the treatment of missing values. PHMSA uniformly codes missing values for records in each of the cost categories as zero. This coding system does not distinguish the crashes with zero-cost elements from crashes with positive costs in cases where the carrier left one or more fields blank. For the purposes of this analysis, it is assumed that the number of observations with missing values is small.

---

[20] The first two cost categories presented here can be used to estimate total property damage costs in a manner similar to that used both in Zaloshnja and Miller (2007) and in Section 2 of this report. For example, the average property damage cost of a HM crash would equal the mean value of damage to the carriers' vehicles plus the mean damage to other property multiplied by the number of other vehicles involved in a HM crash.

## 5.5 MCMIS

The MCMIS Crash File includes the following information:

- Identifying information for the carrier.
- Cargo type classifications.
- HM placard identifier.
- Vehicle configuration (single unit, tractor, etc.).
- County, day, and time of crash.

## 5.6 MATCHING TECHNIQUE

In order to combine the HMIS and MCMIS datasets, a novel matching procedure was developed. Using the county and day-of-crash fields in both datasets, a large number of records from the HMIS database were matched to the MCMIS database. A match was determined if each dataset recorded a single HM crash on a given day in a given county. For many, but not all, county-day combinations there was a single HM crash. The initial HMIS dataset recorded 3,363 HM crashes between 1980 and 2010; of these, 1,151 records were matched in the MCMIS.

Counties with large amounts of CMV traffic have a greater likelihood of experiencing multiple CMV crashes on a single day, and it was not possible to match such crashes. Therefore, the matching procedure may result in selection bias, which would lead to large counties being underrepresented in the matched data. Such large counties may have higher average HM crash costs because they tend to have more passenger vehicle traffic and because individuals living in those counties may reside closer to roads. Analogous tables that use only HMIS data, but don't differentiate by vehicle configuration, are also presented. Statistical tests did not find evidence for systematic differences between the matched and unmatched HMIS samples.

## 5.7 ESTIMATES

A variety of statistics were generated from the databases described above; in addition, corresponding statistical tests were performed to ascertain the precision of the estimates. Using data from the HMIS database, the average cost of damages (the total across all recorded cost categories) was $129,141 (in 2010 dollars). The point estimates are presented in Table 60. The histogram presented in Figure 43 shows the distribution of total damage costs for the entire HMIS sample. As the figure illustrates, crashes most frequently result in damages at the low end of the cost range, but note that there are a substantial number of crashes at the high end of the scale. For clarity, crashes above $1,000,000 in cost have been aggregated into the right-most bar; the number of such crashes was only 37, which should not alter the shape of the distribution appreciably.

Table 60. Distribution of Damages From HM Crashes (2010 Dollars)

| N | Mean | 5th Percentile | 25th percentile | 50th Percentile | 75th Percentile | 95th Percentile |
|---|---|---|---|---|---|---|
| 3,363 | $129,141 | $0 | $12,169 | $63,885 | $139,446 | $402,458 |

Using severity data from the HMIS database, total HM crash costs were further broken down by crash severity level. Table 61 shows that crashes resulting in one or more fatalities are much costlier than crashes that only result in injury or property damages. Note that the value of lost life is not included in the damage costs presented in Table 61 (or any of the other tables). An analysis of variance (ANOVA) test for the equality of means between the three types of crashes yields a F-statistic of 68.21, which is high enough in magnitude to reject the null hypothesis of equal means.

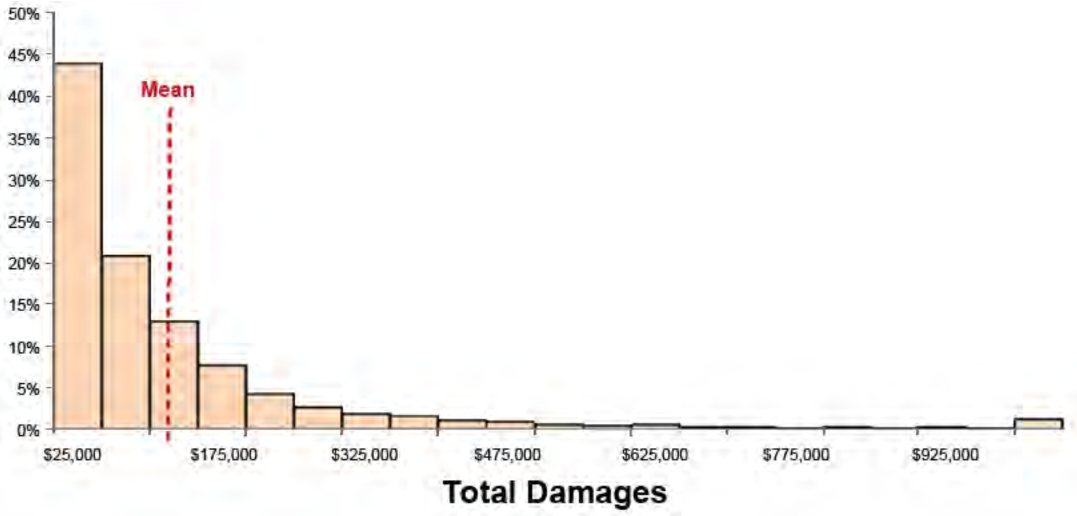


Figure 43. Histogram of Total Damages

Table 61. Average Total Cost of Damages from HM Crashes by Crash Severity (2010 Dollars)

| Severity Level | N | Mean | Standard Error of Mean | *T-statistic |
|---|---|---|---|---|
| Fatal | 279 | $263,775 | $33,283 | 7.93 |
| Injury | 696 | $142,916 | $11,929 | 11.98 |
| PDO | 2,388 | $109,396 | $7,416 | 14.75 |

*The t-statistic presented in this and subsequent tables represents the ratio between the mean and its standard error. This is equivalent to the t-statistic for testing if the mean is equal to zero. The statistic is provided mainly to indicate how precise the estimate of the mean damages is, rather than as a rigorous statistical test.

The total cost of damages across cost categories is presented in Table 62. That table shows that damage to the carrier and cleanup costs were the two largest components of total damages. Recall however that carrier damage is the category that motor carriers have the best estimates of, and that many carriers will self-report damage costs of zero if they are unsure of the true amounts.

**Table 62. Average Cost of Damages from HM Crashes by Category (2010 Dollars)**

| Cost Category | N | Mean | Standard Error of Mean | T-statistic |
|---|---|---|---|---|
| Material | 3,363 | $4,832 | $236 | 20.21 |
| Carrier | 3,363 | $49,582 | $1,160 | 42.74 |
| Property | 3,363 | $18,335 | $3,015 | 6.08 |
| Cleanup | 3,363 | $46,255 | $3,083 | 15.00 |
| Other | 3,363 | $1,936 | $437 | 4.43 |
| Response | 3,363 | $4,020 | $352 | 11.44 |
| Total Damages | 3,363 | $129,141 | $6,477 | 19.94 |

The cost of damage by HM is presented in Table 63. Note that flammable liquids are the most commonly observed HM present in HM crashes. That observation is mostly due to the large number of motor carriers that transport flammable liquids (e.g., gasoline) in the population. The remainder of the categories are observed much less frequently. Thus, while estimates of the mean and t-statistics are provided, they may not be highly accurate for categories rarely observed.

**Table 63. Average Cost of Damages From HM Crashes by HM (2010 Dollars)**

| HM | N | Mean | Standard Error of Mean | T-statistic |
|---|---|---|---|---|
| Flammable Liquids | 1,961 | $159,838 | $7,118 | 22.45 |
| Corrosive Materials | 431 | $115,627 | $33,233 | 3.48 |
| Flammable Gases | 287 | $47,879 | $3,578 | 13.38 |
| Miscellaneous | 210 | $112,453 | $36,032 | 3.12 |
| Non-Flammable Gases | 179 | $71,020 | $7,950 | 8.93 |
| Oxidizers | 122 | $67,830 | $7,357 | 9.22 |
| Toxic and Infectious Substances | 53 | $79,553 | $32,179 | 2.47 |
| Stable Explosives | 38 | $58,994 | $8,578 | 6.88 |
| Flammable Solids | 26 | $56,956 | $11,910 | 4.78 |
| Radioactive Materials | 25 | $45,805 | $16,138 | 2.84 |
| Explosives | 15 | $215,414 | $154,064 | 1.4 |
| Poisonous Gases | 14 | $10,210 | $4,573 | 2.23 |

Table 64 provides detail regarding the match rate between the HMIS and MICMIS databases. Note that almost a third of the HM placard-carrying trucks involved in a crash are identified in the HMIS database. Also note that the mean level of total damages (i.e., the sum of material, carrier, property, emergency response, and cleanup costs) are very similar for both sets of crashes. The mean for damages unmatched in HMIS records is approximately $124,000 while the average for matched records is $137,000. A t-test for the null hypothesis that the means of the two samples are equal indicate that one cannot reject this null hypothesis (t stat = -0.99). A set of equality tests between the individual cost categories (not presented in tabular form) indicate that for all but the carrier damage category, the costs are not statistically different between the two subsets of matched and unmatched data. Although the carrier damage estimates are found to be statistically different, the economic significance of the difference is small: the average carrier damage cost for the unmatched sample is $46,368 while the matched sample has an average of $55,724.

Looking at the matched sample means, the detail provided by the MCMIS database allows a comparison of total costs by vehicle configuration. The matched frequency, mean, median, and standard deviation are provided in Table 65. The table indicates that larger trucks tend to be involved in high-cost crashes, presumably because the vehicles are more valuable and because they tend to carry larger quantities of HM.

**Table 64. Two-Sample T-test for Equality of Means Between Matched and Unmatched Subsamples For HM Damages (2010 Dollars)**

| Variable | In MCMIS? | N | Mean | Standard Error of Mean |
|---|---|---|---|---|
| Total Damages | No | 2,212 | $124,533 | $8,654 |
| Total Damages | Yes | 1,151 | $137,996 | $9,033 |

**Table 65. Average Cost of Damages from HM Crashes by Vehicle Configuration (2010 Dollars)**

| Vehicle Configuration | N | Mean | Standard Error of Mean | T-statistic |
|---|---|---|---|---|
| Single-Unit Trucks (2-Axles, 6 Tires) | 108 | $53,145 | $6,202 | 8.57 |
| Single-Unit Trucks (3+ Axles) | 79 | $118,440 | $19,157 | 6.18 |
| Trucks With Trailers | 135 | $152,226 | $20,440 | 7.45 |
| Tractors With Semi-Trailers | 706 | $143,247 | $8,627 | 16.6 |
| Tractors With Double Semi-Trailers | 59 | $212,785 | $119,331 | 1.78 |

## 5.8 DELAY AND EMISSIONS COSTS

Using the distribution of crash durations and severity for HM crashes (see Figure 42 and Table 61), it is possible to estimate delay, emissions, and fuel costs specific to various kinds of HM crashes. The same process as described in Section 3 is used here. The severity specific durations used for the HM estimates are presented in Table 66.

Table 67 presents net delay stemming from HM crashes and breaks down the results by severity. Similarly, Table 68 presents the monetized costs of delay stemming from HM crashes. These values follow similar patterns to the non-HM crashes. Fatal crashes tend to have the longest delay while Urban functional classes tend to have longer delays than their Rural counterparts.

**Table 66. Probability of Various Closure Durations by Severity for HM Crashes**

| | No Closure | 0-30 Min | 30-60 Min | 1-3 Hrs | 3-6 Hrs | 6-9 Hrs | >9 Hrs |
|---|---|---|---|---|---|---|---|
| **Median Closure** | **0 min** | **15 min** | **45 min** | **90 min** | **4 hrs** | **7 hrs** | **9 hrs** |
| Fatal | 5% | 0% | 5% | 5% | 50% | 32% | 5% |
| Injury only | 29% | 13% | 19% | 18% | 10% | 6% | 5% |
| PDO | 42% | 15% | 17% | 13% | 9% | 3% | 2% |
| **All** | **32%** | **13%** | **17%** | **14%** | **14%** | **7%** | **3%** |

**Table 67. Estimates of Delay by Roadway Type and Severity (Vehicle Hours) for HM Crashes**

| Roadway Type | Fatal | Injury Only | PDO | Average for Roadway Type |
|---|---|---|---|---|
| Urban Interstate/Expressway | 9,146 | 4,176 | 3,073 | 4,229 |
| Urban Arterial | 664 | 268 | 176 | 271 |
| Urban Other | 397 | 176 | 130 | 180 |
| Rural Interstate/Principal Arterials | 648 | 300 | 201 | 294 |
| Rural Other | 136 | 60 | 42 | 60 |
| **Average for All Roadway Types** | **2,217** | **1,004** | **730** | **1,014** |

**Table 68. Estimates of Cost of Delay by Facility Type and Severity for HM Crashes (2010 Dollars)**

| Roadway Type | Fatal | Injury Only | PDO | Average for Roadway Type |
|---|---|---|---|---|
| Urban Interstate/Expressway | $222,808 | $101,656 | $74,797 | $102,942 |
| Urban Arterial | $16,151 | $6,526 | $4,286 | $6,584 |
| Urban Other | $9,672 | $4,290 | $3,171 | $4,378 |
| Rural Interstate/Principal Arterials | $15,779 | $7,298 | $4,885 | $7,166 |
| Rural Other | $3,303 | $1,454 | $1,019 | $1,463 |
| **Average for All Roadway Types** | **$53,991** | **$24,426** | **$17,758** | **$24,693** |

Table 69 presents the net emissions estimates for various facility types, unconditional of the severity of the crash. The net emissions for crashes of differing severity levels are presented in Table 70, Table 71, and Table 72. Those tables indicate that fatal crashes tend to result in greater levels of emissions than injury only crashes. (Note that these tables exclude emissions associated with any potential spills of HMs.)

Table 73 presents the average costs of emissions stemming from HM crashes across severity types. The most expensive type of HM related crash tends to be a fatal crash occurring on an Urban Expressway. As with non-HM crashes, the emissions costs are relatively small compared to the delay costs.

### Table 69. Estimated Net Emissions by Roadway Type for HM Crashes (Short Tons)

| Roadway Type | $CO_2$ | CO | NOx | $PM_{10}$ | $PM_{2.5}$ | $SO_2$ | Total HC | VOC |
|---|---|---|---|---|---|---|---|---|
| Urban Interstate/Expressway | 20.12080 | 0.14181 | 0.03655 | 0.00309 | 0.00299 | 0.00036 | 0.01544 | 0.01521 |
| Urban Arterial | 4.61482 | 0.02916 | 0.00825 | 0.00038 | 0.00036 | 0.00008 | 0.00199 | 0.00193 |
| Urban Other | 1.57938 | 0.00969 | 0.00290 | 0.00011 | 0.00011 | 0.00003 | 0.00056 | 0.00054 |
| Rural Interstate/Principal Arterials | 3.38787 | 0.02226 | 0.01296 | 0.00071 | 0.00069 | 0.00005 | 0.00154 | 0.00151 |
| Rural Other | 1.27565 | 0.00774 | 0.00410 | 0.00021 | 0.00020 | 0.00002 | 0.00050 | 0.00049 |
| **Average for All Roadway Types** | **6.27704** | **0.04265** | **0.01297** | **0.00090** | **0.00087** | **0.00011** | **0.00404** | **0.00397** |

### Table 70. Estimated Net Emissions by Roadway Type for HM Crashes (Short Tons)—Fatal Crashes

| Roadway Type | $CO_2$ | CO | NOx | $PM_{10}$ | $PM_{2.5}$ | $SO_2$ | Total HC | VOC |
|---|---|---|---|---|---|---|---|---|
| Urban Interstate/Expressway | 43.54972 | 0.30693 | 0.07912 | 0.00669 | 0.00646 | 0.00078 | 0.03341 | 0.03293 |
| Urban Arterial | 11.32044 | 0.07153 | 0.02025 | 0.00094 | 0.00090 | 0.00019 | 0.00488 | 0.00473 |
| Urban Other | 3.48922 | 0.02140 | 0.00641 | 0.00024 | 0.00023 | 0.00006 | 0.00123 | 0.00120 |
| Rural Interstate/Principal Arterials | 7.45947 | 0.04902 | 0.02853 | 0.00156 | 0.00151 | 0.00011 | 0.00338 | 0.00332 |
| Rural Other | 2.87989 | 0.01747 | 0.00925 | 0.00048 | 0.00046 | 0.00004 | 0.00113 | 0.00110 |
| **Average for All Roadway Types** | **13.94588** | **0.09458** | **0.02879** | **0.00198** | **0.00191** | **0.00024** | **0.00890** | **0.00874** |

### Table 71. Estimated Net Emissions by Roadway Type for HM Crashes (Short Tons)—Injury Only Crashes

| Roadway Type | $CO_2$ | CO | NOx | $PM_{10}$ | $PM_{2.5}$ | $SO_2$ | Total HC | VOC |
|---|---|---|---|---|---|---|---|---|
| Urban Interstate/Expressway | 19.86942 | 0.14004 | 0.03610 | 0.00305 | 0.00295 | 0.00036 | 0.01524 | 0.01502 |
| Urban Arterial | 4.57443 | 0.02890 | 0.00818 | 0.00038 | 0.00036 | 0.00008 | 0.00197 | 0.00191 |
| Urban Other | 1.54762 | 0.00949 | 0.00284 | 0.00011 | 0.00010 | 0.00003 | 0.00055 | 0.00053 |
| Rural Interstate/Principal Arterials | 3.45009 | 0.02267 | 0.01320 | 0.00072 | 0.00070 | 0.00005 | 0.00156 | 0.00153 |
| Rural Other | 1.26778 | 0.00769 | 0.00407 | 0.00021 | 0.00020 | 0.00002 | 0.00050 | 0.00049 |
| **Average for All Roadway Types** | **6.22111** | **0.04226** | **0.01289** | **0.00089** | **0.00086** | **0.00011** | **0.00400** | **0.00393** |

**Table 72. Estimated Net Emissions by Roadway Type for HM Crashes (Short Tons)—PDO Crashes**

| Roadway Type | $CO_2$ | CO | NOx | $PM_{10}$ | $PM_{2.5}$ | $SO_2$ | TotalHC | VOC |
|---|---|---|---|---|---|---|---|---|
| Urban Interstate/Expressway | 14.61975 | 0.10304 | 0.02656 | 0.00225 | 0.00217 | 0.00026 | 0.01122 | 0.01105 |
| Urban Arterial | 3.00381 | 0.01898 | 0.00537 | 0.00025 | 0.00024 | 0.00005 | 0.00129 | 0.00125 |
| Urban Other | 1.14399 | 0.00702 | 0.00210 | 0.00008 | 0.00008 | 0.00002 | 0.00040 | 0.00039 |
| Rural Interstate/Principal Arterials | 2.30921 | 0.01518 | 0.00883 | 0.00048 | 0.00047 | 0.00003 | 0.00105 | 0.00103 |
| Rural Other | 0.88815 | 0.00539 | 0.00285 | 0.00015 | 0.00014 | 0.00001 | 0.00035 | 0.00034 |
| **Average for All Road Types** | **4.44590** | **0.03026** | **0.00915** | **0.00064** | **0.00062** | **0.00008** | **0.00289** | **0.00284** |

### Table 73. Estimates of Net Emissions Costs by Roadway Type and Severity—HM Crashes (2010 Dollars)

| Roadway Type | Fatal | Injury Only | PDO | Average for Road Type |
|---|---|---|---|---|
| Urban Interstate/Expressway | $4,106 | $1,874 | $1,379 | $1,897 |
| Urban Arterial | $802 | $324 | $213 | $327 |
| Urban Other | $235 | $104 | $77 | $106 |
| Rural Interstate/Principal Arterials | $1,003 | $464 | $310 | $455 |
| Rural Other | $325 | $143 | $100 | $144 |
| **Average for All Roadway Types** | **$1,300** | **$583** | **$417** | **$588** |

Finally, Table 74 and Table 75 present the net excess fuel burn and its associated costs (respectively) for HM crashes. A fatal crash on an Urban Interstate/Expressway typically causes about $8,900 in excess fuel burn costs. While a substantial cost, this represents approximately four percent of the cost of delay for a fatal crash on an Urban Interstate/Expressway. As with non-HM crashes, delay represents a substantially larger share of the cost than either emissions or excess fuel burn.

### Table 74. Estimates of Excess Fuel Burn by Roadway Type and Severity (Gallons)—HM Crashes

| Roadway Type | Fatal | Injury Only | PDO | Average for Road Type |
|---|---|---|---|---|
| Urban Interstate/Expressway | 3609.8 | 1648.38 | 1212.87 | 1668.92 |
| Urban Arterial | 1007.88 | 407.3 | 267.46 | 410.89 |
| Urban Other | 302.76 | 134.48 | 99.41 | 137.2 |
| Rural Interstate/Principal Arterials | 675.12 | 312.33 | 209.05 | 306.68 |
| Rural Other | 274.55 | 120.84 | 84.66 | 121.6 |
| **Average for All Roadway Types** | **1191.42** | **531.31** | **379.11** | **535.88** |

### Table 75. Estimates of Cost of Excess Fuel Burn by Roadway Type and Severity—HM Crashes (2010 Dollars)

| Roadway Type | Fatal | Injury Only | PDO | Average for Road Type |
|---|---|---|---|---|
| Urban Interstate/Expressway | $8,902 | $4,061 | $2,988 | $4,113 |
| Urban Arterial | $2,474 | $1,000 | $656 | $1,008 |
| Urban Other | $744 | $330 | $244 | $337 |
| Rural Interstate/Principal Arterials | $1,668 | $771 | $516 | $757 |
| Rural Other | $680 | $300 | $210 | $301 |
| **Average for All Roadway Types** | **$2,935** | **$1,308** | **$934** | **$1,320** |

[This page intentionally left blank.]

# REFERENCES

1. AASHTO, *A Policy on Geometric Design of Highways and Streets*, 5th ed., Washington, DC: American Association of State Highway and Transportation Officials (2004).
2. Bureau of Transportation Statistics, “National Household Travel Survey: Pre- and Post-9/11 Data Documentation,” Washington, D.C.: USDOT/BTS (2009).
3. Byun, John, “A New Generation Air Quality Dispersion Model,” presented at TRB, US DOT/FHWA, Baltimore, MD (January, 2007).
4. Chin, S.M., O. Franzese, D. Greene, and H. Hwang, “Temporary Losses of Highway Capacity and Impacts on Performance: Phase 2,” prepared for Oak Ridge National Laboratories and University of Tennessee, Oak Ridge, TN: U.S. Department of Energy (November, 2004). http://www.ornl.gov/~web- works/cppr/y2001/rpt/121341.pdf.
5. Craft, Ralph, “The Large Truck Crash Causation Study,” prepared for USDOT/FMCSA, Washington, D.C.: (July, 2007). http://www.fmcsa.dot.gov/facts-research/research-technology/analy- sis/FMCSA-RRA-07-017.htm.
6. Davis, Stacy C., Susan W. Diegel, and Robert G. Boundy, *Transportation Energy Data Book*, 29th ed., prepared for U.S. Department of Energy, Oak Ridge, TN: Oak Ridge National Laboratory (July, 2010).
7. Dunn, Walter, R.A. Reiss M., and Steven P. Latoski, “Roadway Incident Diversion Practices: A Synthesis of Highway Practice 279,” National Cooperative Highway Research Program, Washington, D.C.: Transportation Research Board (1999).
8. Econometrica, Inc., “Update Plan for Study of Costs of Large and Medium Truck Crashes,” Washington, D.C.: Econometrica (November 19, 2008).
9. EnvironmentalChemistry.com, “USDOT Hazardous Materials Transportation Placards.” http://environmentalchemistry.com/yogi/hazmat/placards/.
10. Fann, Neal, and David Risley, “The Public Health Context for PM2.5 and Ozone Air Quality Trends,” *Air Quality, Atmosphere & Health*, 2:3 (September, 2009), pp. 169-176.
11. Federal Highway Administration, *Functional Classification Guidelines: Concepts, Criteria and Procedures*, Washington, D.C.: USDOT/FHWA (1989). http://www.fhwa.dot.gov/planning/fcsec1_1.htm.
12. Federal Highway Administration, “Highway Economic Requirements System-State Version: Technical Report,” prepared for FHWA, Cambridge, MA: USDOT/Volpe Center (August, 2005).
13. Federal Highway Administration, *Highway Performance Monitoring System Field Manual*, Washington, DC: USDOT/FHWA (May, 2005).
14. Federal Highway Administration, Nationwide Personal Transportation Survey: “Special Reports on Trip and Vehicle Attributes,” 1990 NPTS Reports, Washington, D.C.: USDOT/FHWA, (February, 1995).

15. Federal Motor Carrier Safety Administration, “Large Truck Crash Facts 2005,” Washington, D.C.: USDOT/FMCSA Analysis Division (February, 2007). http://www.fmcsa.dot.gov/facts-research/research-technology/report/Large-Truck-Crash-Facts-2005/Index-2005LargeTruckCrashFacts.htm.
16. Federal Motor Carrier Safety Administration, Report to Congress on the Large Truck Crash Causation Study, Washington, D.C.: USDOT/FMCSA (November, 2005).
17. Flieger, Theresa, Adam Klauber, Jose Mantilla, and Paul Zebe, Environmental Costs of Commercial Motor Vehicle (CMV) Crashes: Estimation Report, prepared for USDOT/FMCSA, Cambridge, MA: USDOT/Volpe Center (March, 2007).
18. Greene, William H., Econometric Analysis, 5th ed., Englewood Cliffs, NJ, Prentice Hall (2003).
19. Hahn, Robert W., “Government Analysis of the Benefits and Costs of Regulation,” *Journal of Economic Perspectives*, 12:4 (Fall, 1998), pp. 201-210.
20. Hedlund, James, and Daniel Brower, “Using LTCCS Data for Statistical Analysis of Crash Risk,” Washington, D.C.: US DOT/FMCSA (January, 2006). http://www.fmcsa.dot.gov/facts-research/research-technology/analy- sis/ltccs.htm.
21. Hershey, William, “Will Faster Trucks Mean More Fatalities?” *Dayton Daily News*, (April 1, 2009).
22. Interagency Working Group on Social Cost of Carbon, Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, Washington, D.C.: IWGSCC (2010).
23. Klauber, Adam, and Paul Zebe, “Environmental Costs of Commercial Motor Vehicle (CMV) Crashes: Proof of Concept Enhanced Estimation,” prepared for USDOT/FMCSA, Cambridge, MA: USDOT/Volpe Center (September, 2008).
24. McCubbin, Donald R., and Mark A. Delucchi, “The Health Costs of Motor-Vehicle-Related Air Pollution,” *Journal of Transport Economics and Policy*, 33:3 (1999), pp. 253-286.
25. Microsoft Corp., SQL Server 2008 Version R2, Redmond, WA: Microsoft Corp (2008).
26. Miller, Ted R., “The Costs of Highway Crashes,” prepared for FHWA, Washington, DC: The Urban Institute (October, 1991).
27. Moses, Leon N., and Ian Savage, “A Cost-Benefit Analysis of US Motor Carrier Safety Programmes,” *Journal of Transport Economics and Policy*, 31:1 (January, 1997), pp. 51-67.
28. Moses, Leon N., and Ian Savage (eds.), *Transportation Safety in an Age of Deregulation*, New York, NY: Oxford University Press (1989).

29. Murray, Dan, Sandra Shackelford, and Amy Houser, “Analysis of Benefits and Costs of Roll Stability Control Systems for the Trucking Industry,” prepared for USDOT/FMCSA, Arlington, VA: American Transportation Research Institute and Federal Motor Carrier Safety Administration (February, 2009). http://www.fmcsa.dot.gov/facts-research/research-technology/report/09-020- rp-roll-stability.pdf.

30. O’Day, James, Robin Ruthazer, and Tom Gonzales, *An In-Depth Study of Truck Fire Accident Data*, Ann Arbor, MI: The University of Michigan Transportation Research Institute (April, 1985).

31. Pope, C. Arden, III, Richard T. Burnett, and Michael J. Thun, “Lung Cancer, Cardio-pulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution,” *Journal of the American Medical Association*, 287:9 (March, 2002), pp.1132-1141.

32. Preusser, David F., Allan F. Williams, James L. Nichols, Julie Tison, and Neil K. Chaudary, Effectiveness of Behavioral Highway Safety Countermeasures, NCHRP Report 622, Washington, D.C.: Transportation Research Board (2008).

33. Recker, Wilfred W., Thomas F. Golob, Paula D. Nohalty, and Chang-Wei Hsueh, “The Congestion Effects of Truck-Involved Urban Freeway Collisions,” paper for TRB, Washington, DC: authors (January, 1990).

34. Teal, Roger F., *Estimating the Full Economic Costs of Truck Incidents on Urban Freeways*, Irvine, CA: Institute of Transportation Studies (1988).

35. Transportation Research Board, Transportation Research Board: HCM 2000, Washington, D.C.: TRB (2000).

36. U.S. Department of Transportation, Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis, Washington, DC: USDOT/OST (September 28, 2011).

37. U.S. Department of Transportation, U.S. Code of Federal Regulations - 49 CFR, Transportation Washington, D.C.: National Archives and Records Administration (October, 2002). http://www.access.gpo.gov/cgi-bin/cfrassem-ble.cgi?title=200249.

38. U.S. Department of Transportation, Office of Inspector General, Oversight of the Commercial Driver’s License Program: Federal Motor Carrier Safety Administration, Washington, DC: USDOT/OIG (February, 2006).

39. U.S. Energy Information Administration, “Petroleum Marketing Monthly,” DOE/EIA (April, 2011).

40. U.S. Environmental Protection Agency, Draft Motor Vehicle Emission Simulator (MOVES) 2009: Software Design and Reference Manual, Washington, D.C.: US EPA, (2009).

41. U.S. Environmental Protection Agency, User’s Guide to MOBILE6.1 and MOBILE6.2 Air and Radiation, Washington, D.C.: US EPA (August, 2003).

42. Viscusi, W. Kip, “The Dangers of Unbounded Commitments to Regulate Risk,” in Hahn, Robert W. (ed.) Risks, Costs, and Lives Saved: Getting Better Results From Regulation, New York, NY: Oxford University Press (1996), pp. 135-166.

43. Zaloshnja, Eduardo, and Ted R. Miller, “Costs of Large Truck-Involved Crashes in the United States,” *Accident Analysis and Prevention*, 36:(2004), pp. 801-808.

44. Zaloshnja, Eduard, and Ted R. Miller, “Unit Costs of Medium and Heavy Truck Crashes,” prepared for USDOT/FMCSA, Calverton, MD: Pacific Institute for Public Policy Research (March, 2007).

45. Zaloshnja, Eduard, Ted R. Miller, and Rebecca Spicer, “Costs of Large Truck- and Bus-Involved Crashes,” prepared for USDOT/FMCSA, Landover, MD: Pacific Institute for Public Policy Research (December, 2000).

46. Zhai, H., H.C. Frey, and N.M. Rouphail, “A Vehicle Specific Power Approach to Speed and Facility-Specific Emissions Estimates for Diesel Transit Buses,” *Environmental Science & Technology*, 42:1 (2008), pp. 7985-7991.