Naturalistic Driving Data Baseline for Automated Driving System-Equipped Commercial Motor Vehicles

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

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FOREWORD

The rapid development of technology in automated vehicles could provide significant improvements in commercial motor vehicle highway safety and efficiency. This report provides lagging baselines (measures of crashes and near crashes that represent outcomes ADS technologies may attempt to mitigate) and leading baselines (measures of human driver performance that ADS technologies may attempt to emulate, meet, or exceed; or that may form bases of comparison when developing ADS maneuvering capabilities). The lagging baseline is derived from 3.44 billion vehicle miles traveled and includes crash rates covering more than 3,700 crashes distributed across 10 operational design domains within the United States. The leading performance baselines are derived from over 3.2 million miles of continuous driving matched to highway routes (e.g., I-10, I-75), which may be useful to developers of automated driving systems (ADS) for commercial motor vehicles (CMVs) in defining commonly shared, non-proprietary vehicle maneuver attributes. These attributes, such as lane deviation and following distance, could be established over time and eventually refined into appropriate criteria for ADS-equipped CMVs during testing and deployment cycles.

NOTICE

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16. Abstract

Automated driving system (ADS) equipped commercial motor vehicles (CMVs) have the potential to reduce crashes by eliminating driver inattention and negative behavior errors. Assessing the effectiveness of ADS-equipped CMVs requires an understanding of baseline safety performance measures for non-equipped CMVs. This study analyzed naturalistic event field data including over 3.44 billion miles of Class 8 CMV operations to produce a lagging performance baseline of crashes and near-crashes. This baseline represents rates produced over long periods of time across large numbers of CMVs. The event data for the lagging baseline was map-matched to 10 specific highway operational design domains (ODDs), including all U.S. highways that fit the study criteria and appeared in the data, and the nine specific highways where many of the data were collected.

This study also analyzed naturalistic continuous field data including 3.2 million miles of Class 8 CMV operations to produce a leading performance baseline of typical CMV maneuvers. This baseline represents rates of vehicle maneuvers—that is, how frequently a given maneuver occurs per vehicle mile traveled within specific domains. The leading baseline was developed from six types of maneuvers including speed behavior, longitudinal deceleration, following distance, lateral acceleration, lane deviation, and lane stability. Maneuvers were matched across 10 U.S. highway ODDs, 7 speed limit categories, and 7 number-of-lane categories. A reference set of leading baseline performance was also developed for a collection of Canada highway data. These data may be valuable for creating baselines applicable to northern U.S. transit corridors or to traffic between the United States and Canada

This study also resulted in a public-use data tool for querying event rates based on a range of selectable parameters.

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SI* (MODERN METRIC) CONVERSION FACTORS

Symbol	When You Know	Multiply By	To Find	Symbol
Approximate Conversions to SI Units				
		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 (volumes greater than 1,000L 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 (exact degrees)		
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	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

Symbol	When You Know	Multiply By	To Find	Symbol
Approximate Conversions from SI Units				
		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 (exact degrees)		
°C	Celsius	1.8c+32	Fahrenheit	°F
		Illumination		
Lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		Force and 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.)

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

Acronym	**Definition**
AASHTO	American Association of State Highway Transportation Officials
ADAS	advanced driver assistance system
ADS	automated driving systems
CNTD	Canadian Naturalistic Truck Dataset
CMV	commercial motor vehicle
DAS	data acquisition system
DUL	data use license
FAST DASH	FMCSA's Advanced System Testing utilizing a Data Acquisition System on the Highways
FMCSA	Federal Motor Carrier Safety Administration
IRB	Institutional Review Board
LatAccel	lateral acceleration
LonDecel	longitudinal deceleration
LD	lane deviation
NHTSA	National Highway Traffic Safety Administration
OBMS FOT	Onboard Monitoring Systems Field Operational Test
ODD	operational design domain
OEDR	object and event description and response
OR	odds ratio
QA	quality assurance
SCE	safety-critical event
SHRP 2	Second Strategic Highway Research Program

Acronym	**Definition**
TIGER	Topologically Integrated Geographic Encoding and Referencing (system)
TTC	time to collision
USDOT	United States Department of Transportation
VMT	vehicle miles traveled
VTTI	Virginia Tech Transportation Institute

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EXECUTIVE SUMMARY

BACKGROUND AND PURPOSE

Automated driving technologies are developing rapidly. In the trucking domain, key on-road applications being demonstrated or considered for market use include platooning (i.e., two or more trucks electronically linked in a convoy); exit-to-exit (i.e., human driver alternates first and last miles with self-driving trucks on long limited access highway trips); traffic jam assist; automated movement in queue (at ports or distribution centers); automated trailer backing; and parcel delivery automation.

Some automated driving system (ADS) equipped commercial motor vehicle (CMV) applications are relatively technologically mature within constrained highway environments, offering significant potential safety benefits, given that human driver error is a contributing factor in the majority of crashes. Still, the safety performance of these technologies remains a concern for large-scale market use.

To accurately determine the impact of ADS-equipped CMVs on the transportation system, commonly accepted benchmarks or baselines are needed to evaluate their safety. One natural baseline is the current safety performance of human drivers. The purpose of this study was to establish baselines for human CMV drivers in order to compare the performance of human drivers with platooning CMVs and ADS-equipped CMVs. These truck-related baseline rates of driving performance are unique to this study and these data are the first of its kind in the public domain.

PROCESS

The research team developed a set of "**lagging**" and "**leading**" safety performance baselines to support the development, testing, and deployment of highway platooning and ADS-equipped CMVs. The **lagging baseline** derives from 3.44 billion vehicle miles traveled and includes crash rates covering more than 3,700 crashes. The **leading baselines** derive from over 3.2 million miles of continuous driving data matched to detailed map information, allowing analysis of maneuvers based on roadway characteristics.

The lagging and leading baselines were evaluated across a set of **operational design domains (ODDs)**. Operational design domains are operating conditions that ADS systems are designed for, such as roadway type.[*] The ODDs in this study were divided, limited-access highways within the interstate highway system, distinguished by interchanges.[1]

[*] Operational Design Domain -- *Operating* conditions under which a given *driving automation system* or *feature* thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics. SAE International, April 2021.

A breakdown of the lagging and leading baselines for the ODDs is shown in Figures ES-1 and ES-2.

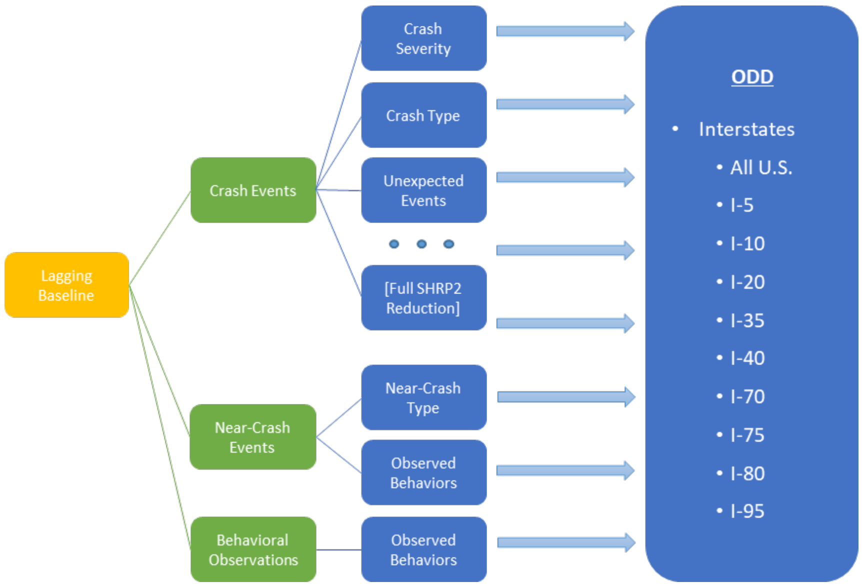

Figure ES-1. Flow chart of lagging baseline computed from vehicle control behavior. Each behavioral baseline is further defined under a different ODD.

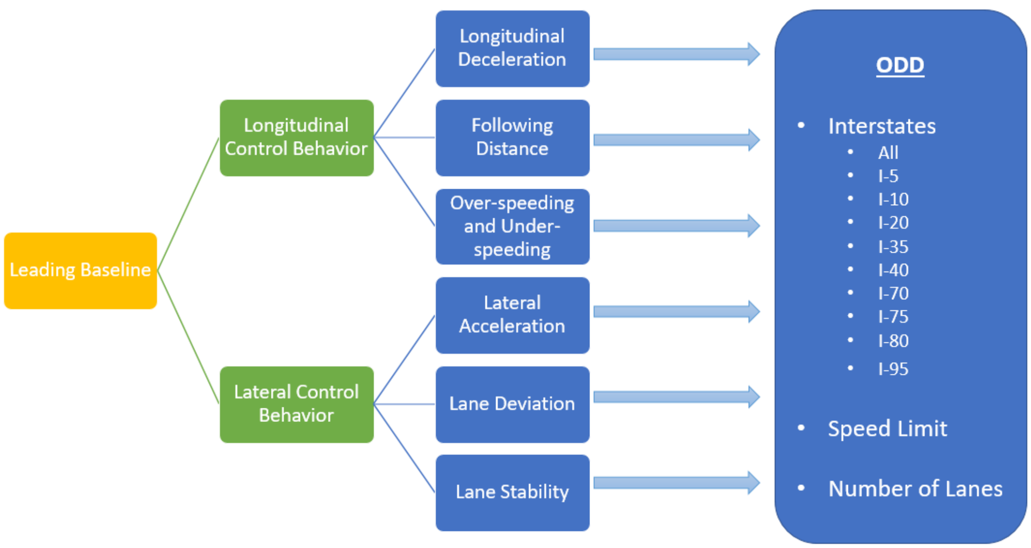

Figure ES-2. Flow chart of leading baseline computed from vehicle control behavior. Each behavioral baseline is further defined under a different ODD.

METHODOLOGY

Lagging Baseline

Data from an onboard monitoring system vendor, SmartDrive Systems, Inc., collected over a 2-year period beginning August 2016, were used to develop the lagging baseline. The onboard monitoring systems record kinematic and video data from CMVs, using crash investigation research dictionaries developed for the U.S. Department of Transportation (USDOT) and the National Academy of Sciences (e.g., the Second Strategic Highway Research Project [SHRP 2]). Additionally, the crashes were matched to nine highway ODDs. A summary of the vehicle miles traveled (VMT) for the different ODDs is shown in Table ES-1.

Table ES-1. VMT for the highway ODDs in the lagging performance baselines

Highway ODD	VMT
All highways	3,441,694,085
Interstate 5	99,105,041
Interstate 10	269,502,657
Interstate 20	236,840,758
Interstate 35	101,004,018
Interstate 40	329,460,656
Interstate 70	157,890,247
Interstate 75	236,029,129
Interstate 80	181,639,244
Interstate 95	156,858,510

Leading Baseline

Crash rates alone cannot measure the safety or efficacy of ADS operation as they could produce misleading conclusions, limiting testing that slows progress or delaying the use of ADS features. The Rand Corporation report, *Measuring Automated Vehicle Safety,* describes leading baseline vehicle measures as "objective, physics-based, available using current technology, and reflective of the official and unofficial rules of the road."[2]

The leading baselines were computed to capture the average performance of human-operated trucks on interstates; the ODD was highway driving, creating consistent metrics. Measured maneuvers included longitudinal control (e.g., longitudinal deceleration, following distance, and average speed relative to posted speed limits) and lateral control (e.g., lateral acceleration, lane deviation, and lane stability).

These leading baseline performance metrics are intended to meet the needs of developers who want to reference common and frequent vehicle maneuvers when testing ADS-equipped CMVs. They are reproducible by second or third parties for verification and can be non-proprietary in their raw form.

RESULTS/FINDINGS

This report identifies significant differences in crash and near crash rates in different ODDs, illustrating the importance of granular baselines with which to evaluate ADS-equipped CMV performance (Table ES-2). These results can be applied to answer the question, “How many crashes today might be mitigated by the introduction of an ADS-equipped CMV?” For example, most or all driver inattention behaviors that degrade the safety performance of human-operated CMVs would be mitigated by CMV ADS.

Table ES-2. Overall crashes per 100 million VMT by highway ODDs

Highway ODD	Overall Crash Rate
All Highways	109.9
Interstate 5	98.9
Interstate 10	85.3
Interstate 20	91.2
Interstate 35	131.7
Interstate 40	79.5
Interstate 70	119.7
Interstate 75	80.5
Interstate 80	109.0
Interstate 95	136.4

The results enable specific comparisons between ADS-equipped CMV performance and current human driver performance. They also allow for an analysis of crashes and near crashes by likely cause, facilitating estimates of how many and which crashes ADS technologies are likely to prevent or mitigate. Highlights are as follows:

- **The 29 percent of crashes identified in the study as involving driver error** represent a significant opportunity for ADS technologies to increase safety on the highways.
- **The two most frequent crash types on all U.S. highways were** conflict with an object in the roadway and conflict with a vehicle in an adjacent lane, both having rates of 28.4 crashes per 100 million VMT.

- **In a majority of crashes involving Class 8 trucks with interior cameras,** drivers were not observed to be involved in secondary tasks. Similarly, in a majority of crashes drivers were not observed to be engaged in negative driving behaviors.
- **The most common unexpected event identified during crashes** involved debris hitting the CMV or an animal/pedestrian running in front of the vehicle on the highway.
- **The majority of crashes occurred during dry, clear, and daylight conditions.** These conditions fit into the ODD profile of near-term deployment of ADS-equipped CMVs.
- **Deceleration rates and instances of shorter following distances both increased with lower speed limits,** suggesting tighter-packed and more variable traffic. This tendency, along with discrepancies between posted speed limits and typical speed behavior, highlights the complexity of designing an ADS able to function smoothly alongside human drivers and demonstrate "roadmanship" (interacting well with other vehicles), in addition to compliance with posted speed limits and pre-set rules about following distance, merging, and other maneuvers.

SUMMARY

Lagging performance measures, such as crashes, can serve as an important measure of safety for human-operated and ADS-equipped CMVs. This study delivered a baseline of observed crash rates and observed near-crashes for Class 8 trucks on specific highway ODDs across the United States. Leading performance measures, such as longitudinal (e.g., following distance) and lateral (e.g., lane deviation) maneuvers, can also provide objective and currently available measures of real-time performance.

Developers, evaluators, regulators, and policymakers may choose to apply such measures to compare ADS and human performance, and assess changes in human driving performance as a result of increased use of ADS technologies.

The research tool created for deriving these specific lagging and leading baseline measures is now available upon request to the public and in the future will be posted on the FMCSA Analysis, Research & Technology website.

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1. INTRODUCTION

Automated driving technologies are developing rapidly. In the trucking domain, key on-road applications being demonstrated or considered for market use include platooning (i.e., two or more trucks electronically linked in a convoy); exit-to-exit (i.e., human driver alternates first and last miles with self-driving truck on long limited access highways); traffic jam assist; automated movement in queue (at ports or distribution centers); automated trailer backing; and parcel delivery automation.

Some automated driving system (ADS) equipped commercial motor vehicle (CMV) applications are relatively technologically mature within constrained highway environments, offering significant potential safety benefits, given that human driver error is a contributing factor in the majority of crashes.[3] Still, the safety performance of these technologies remains a concern for large-scale market use.

To accurately determine the impact of ADS-equipped CMVs on the transportation system, commonly accepted benchmarks or baselines are needed to evaluate their safety. One natural baseline is the current safety performance of human drivers.[4] The purpose of this study was to establish baselines for human CMV drivers in order to compare the performance of human drivers with platooning CMVs and ADS-equipped CMVs. These truck-related baseline rates of driving performance are unique to this study and these data are the first of its kind in the public domain.

1.1 DATA

Lagging baselines for human driver performance (see Section 1.3.1) were calculated based on continuous commercial truck naturalistic driving data collected by an onboard monitoring system vendor, SmartDrive Systems, Inc., and the research team at the Virginia Tech Transportation Institute (VTTI). The vendor provided naturalistic kinematic triggered event data covering 2 years and 3,781 naturalistic truck crashes. Leading baselines were calculated from continuous driving performance data collected during previous research studies (see Section 1.3.2). The lagging and leading baselines were evaluated across a set of Operational Design Domains (ODDs), which are operating conditions that ADS systems are designed for, such as roadway type (see Section 2.2).

1.2 DATA PROCESSING

The research team conducted the following analytic approaches and data processing methods:

- The recorded naturalistic Global Positioning System (GPS) information in the data were matched with road segments on a digital map (from HERE Technologies) using code developed by the research team. Afterward, new algorithms were developed to select defined subsets of the continuous data (e.g., highway driving only).

- The raw radar and camera lane departure signals were processed to identify key braking and lane change maneuver scenarios and their prevalence in naturalistic data. This step measured human behaviors related to following distance and lane deviation.
- The frequencies and types of safety related events in the defined operational design domains (ODDs) were calculated across multiple datasets to establish baseline safety performance for ADS-equipped CMVs.
- The frequencies and rates of driving behavioral indicators that reflect normal driving characteristics were calculated—for example, the typical following distances or braking patterns of human operated trucks during interstate driving.
- Analysis was performed to determine whether variation in the defined ODD changes these rates and frequencies—for example, whether lane keeping behaviors changes with the number of lanes present on a given road.
- Representative benchmarks of behavioral event incidence during crash, near-crash, and non-crash events (e.g., speeding or failure to maintain safe following distance) were developed.
- Crash causation elements on a subset of fully annotated crash events were examined to identify the proportion of potentially ADS-preventable crashes in the highway ODD based on the Crash Trifecta Model (see Section 3.9).

1.3 BASELINES

Using the approaches described above, the research team developed a set of lagging and leading safety performance baselines to support the development, testing, and deployment of highway platooning and ADS-equipped CMVs.

1.3.1 Lagging Baselines

The lagging baseline is based on crash and near-crash events, where each safety metric is weighted by how strongly it relates to crash involvement and near-crash events. Near-crash events were included for several reasons: (1) near-crashes occur more frequently than crashes, (2) the factors present in near-crashes are also commonly found in crashes, and (3) near-crashes are, like crashes, complex events, and developers of ADS-equipped CMVs may have only limited tools for eliminating near-crash scenarios in the future. In general, the lagging performance baseline metrics are built upon case study analysis.

1.3.2 Leading Baselines

The leading baseline is based on typical levels of human driving performance for Class 8 tractor-trailers on highways. Leading baseline metrics defined in this report mainly include speed behavior, longitudinal deceleration, lateral acceleration (left/right), following distance, and lane deviation behaviors. These leading baseline performance metrics can be classified under the category of "roadmanship," which is described in the report *Measuring Automated Vehicle Safety* by the Rand Corporation as, "[capturing] the ability to drive on the road safely without creating hazards and responding well (regardless of legality) to the hazards created by others. The concept centers on whether the vehicle 'plays well with others,' even if others are not around."[5] According to the same report, measures of roadmanship should be objective, physics based, available via existing technology, and reflective of official and unofficial rules of the road.

These leading baseline performance metrics are intended to meet the needs of developers who want to reference common and frequent vehicle maneuvers when testing ADS-equipped CMVs. One common leading performance metric omitted from this report is ADS disengagement. This metric is omitted because of inherent weaknesses in using disengagement as an objective metric. A more in-depth discussion of disengagements is provided in the Rand Corporation report cited above.

Aggressive behaviors, impaired behaviors (e.g., fatigue or alcohol), and distracted driving are commonly referred to as leading performance measures, but these were not treated as leading performance measures in this report. Individually or combined, these behaviors increase the odds that a crash will occur. When combined with an unexpected event (e.g., animal in the road or the sudden stop of lead vehicle), they may increase the odds of a higher severity crash.[6] But these measures are not generally applicable to the development of ADS-equipped CMVs. Developers of ADS-equipped CMVs strive to design ADS technologies that perform consistently and predictably, and match or exceed the performance of humans operating normally.

1.4 APPLICATIONS

The lagging and leading baselines were applied to two automated CMV applications: platooning and ADS-equipped CMVs. Automated driving functions are commonly classified based on their level of automation, as defined by SAE.[7] The SAE levels (1 through 5) represent the extent to which the system relies on the human driver as a fallback, with higher levels indicating reduced and no reliance.[8]

1.4.1 Platooning Tractor-Trailers

The first automated vehicle application considered in this study is platooning. Platooning involves SAE Level 1[9] automation that allows multiple trucks to safely travel together at closer headways than those used by human drivers. During active platooning, the automated system monitors the truck's headway and regulates it by controlling the throttle, and the driver maintains responsibility for steering and other tasks. Platooning vehicles rely on a range of advanced driver-assistance system (ADAS) features that are marketed for highway use to enhance safety and efficiency, such as automatic emergency braking and pairing.

According to Crane et al., "Platooning depends fundamentally on three technologies: 'connected braking,' Forward Collision Avoidance and Mitigation…, and disc brakes."[10] In addition, Crane et al. identify two crash scenarios specific to platooning: "Rear truck colliding with the front truck when the front truck initiates emergency braking to avoid colliding with a vehicle ahead," and "Rear truck colliding with a cut-in vehicle if the cut-in vehicle brakes significantly while in between platooning trucks."[11]

1.4.2 ADS-equipped CMV Tractor-Trailer

The second automated vehicle application considered in this research is Level 4 ADS-equipped CMVs. Level 4 ADS-equipped CMVs are capable of performing the dynamic driving task within the vehicle's ODD. Though this study does not consider SAE Levels 2 and 3, some Level 2 functionality (e.g., lateral monitoring and control) would necessarily be incorporated within the ADS.

At SAE Level 4, the ADS is responsible for monitoring and reacting to its environment without human intervention. Relevant crash scenarios for ADS-equipped CMVs include longitudinal and lateral vehicle-to-vehicle interactions. This study did not investigate factors or effects related to a CMV driver responding to a failure in a future ADS by urgently pulling off the highway or continuing at low speed to the next exit or emergency pull-off zone.

1.5 CONSIDERATIONS

Establishing a baseline for ADS-equipped CMVs is complicated by the probability that they will share roads with human drivers during testing and during at least early phases of deployment. This requires a baseline to account for human error manifesting through surrounding vehicle interactions; a baseline cannot ignore the possibility of human error altogether. The focus instead should lie on what factors the ADS itself does change. The baseline therefore ought to establish the number of crashes that will be affected by the ADS for the vehicle type and ODD in question, where the crash resulted from negative CMV driver behavior.

When establishing the number of crashes present within any ODD, it is important to factor in the percentage of actual crashes versus reported crashes. Developers of ADS-equipped CMVs have been required to report every actual crash. But between 15.4 and 59.7 percent of various types of crashes involving human operated vehicles go unreported, with non-reporting rates tending higher for property-damage only crashes and lower for injury crashes. (Fatal crashes, based on prior research, are consistently reported.) [12-13] The actual rates of Class 8 CMV crashes are foundational to any reliable baseline of lagging performance. Notably, the approach taken in this report does not require correction because crash rates are based on observed and verified crashes and near-crashes from in-vehicle kinematic monitoring and video systems; its sample population, unlike the general population of motor vehicles, was directly observed during data collection.

It is also important to account for how ADS-equipped CMVs will interact with conventional, non-ADS vehicles. Examples from current deployments suggest that the ADS should be cautious, especially while merging into traffic or changing lanes. Additionally, it is reasonable to assume that ADS-equipped CMVs will be involved in crashes—particularly in the near future when sharing the road in a mixed automation environment. Some factors, such as unexpected events, will need to be addressed gradually as edge cases come to light.

This report proposes an approach combining lagging and leading baselines to develop safety performance criteria for ADS-equipped CMVs, based on data from human-operated Class 8 CMVs. The lagging performance metrics are necessary to build social confidence about ADS-equipped CMVs. However, the number of events and accumulated mileage required to make the safety case are not practical for granular test performance tracking, nor are lagging baselines conducive to the iterative process of software and hardware improvements because each generation would reset data collection.[14] The leading performance baseline is one solution to the problem with crash-only lagging performance safety metrics. References of typical lane position, speed, following distance, and related normal driving metrics may provide a practical baseline for ADS-equipped CMVs for most of their highway operating miles.

Relying on a combination of lagging and leading indicators could lead to realistic, measurable performance criteria for ADS-equipped CMVs that are acceptable to the public and developers. Such an approach would indicate which safety solutions that ADS-equipped CMVs can deliver and provide a reliable roadmap for future development.

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2. METHODOLOGY

2.1 OVERVIEW

Existing and new parameters were applied to previously collected Class 8 truck naturalistic data. The data were collected from different data acquisition systems and came from different fleets operating in different geographic regions. The data were selected based on a review of applicable datasets available to the research team. Data acquisition systems did not collect precisely the same data from all fleets; business practices may limit what fleets are focused on capturing; and some driver behaviors were not identified by the vendor when multiple behaviors were present. The set of analysis questions used to review the available data is provided in Appendix A.

The naturalistic event data were collected by onboard monitoring systems over 2 years (August 19, 2016 to August 18, 2018) on cargo-delivering Class 8 trucks. CMVs in 331 fleets covered 3.44 billion highway miles during the 2-year operational and collection period.

The naturalistic continuous data on cargo-delivering fleets were collected across 2011–17 in six separate research collections funded by the Federal Motor Carrier Safety Administration (FMCSA). For the datasets housed by the research team, an initial selection was made based on (1) the age of the data (more recent than 2009); (2) a requirement for continuous data collection; and (3) a focus on large trucks and long-haul operations (due to the focus on ADS-equipped CMVs operating on highways). This resulted in the selection of six in-house datasets for further analysis, obtained from the following studies: (1) FMCSA's Advanced System Testing utilizing a Data Acquisition System on the Highways (FAST DASH) study 1; (2) FAST DASH study 2; (3) FAST DASH study 4; (4) the Onboard Monitoring Systems Field Operational Test, evaluation 1 (OBMS FOT 1); (5) the Onboard Monitoring Systems Field Operational Test, evaluation 2 (OBMS FOT 2); and (6) the Canadian Naturalistic Truck Dataset (CNTD). To keep the leading baseline data on the continuous data applicable to U.S. highways, the five datasets collected in the U.S. are treated here in the main report results. The leading baseline measures from the CNTD are provided separately in Appendix E.

Due to structural differences between the event and continuous datasets, each set applies to different research questions:

1. Naturalistic Event Data: What are the rates of crashes, near-crashes, and other negative behaviors for commercial truck driving on continental U.S. highway operations?
2. Naturalistic Continuous Data: What are the rates of typical commercial truck driving behaviors and maneuvers in continental U.S. highway operations?

The data from both sources were map-matched and organized to constrain analysis to typical activities, which are referred to as cases, and exposure by vehicle miles traveled (VMT) within a divided and restricted-access highway. These highways within the continental U.S. made up the ODD(s) studied.

2.2 OPERATIONAL DESIGN DOMAIN (ODD)

The naturalistic event data were matched to the Topologically Integrated Geographic Encoding and Referencing (TIGER) system to characterize roadway type. For the purposes of this study, only primary roads, labeled as S1100, are included in the ODDs. Primary roads are defined as divided, limited-access highways within the interstate highway system or under State management, and they are distinguished by the presence of interchanges.[15] These highways are accessible by ramps and may require stops at toll booths.

The naturalistic continuous data replicate TIGER's system of primary roads through use of controlled access and divided roadway parameters. A controlled access road is multi-direction digitized—meaning each driving direction is modeled as separate polylines, has no crossings at grade, and is accessible by ramps or rest areas only as defined by the map-matching parameters.

The research team organized the collection of naturalistic data by 10 national highway categories. The highways were selected based on three criteria:

1. Road sections were limited by contract with the vendor to 10 ODDs at sufficient granularity for data privacy.
2. The selected highways are likely sites for future divided and limited-access highway deployments of automated applications.
3. Road section data were contained in both the event and continuous datasets.

The 10 ODDs included all primary roads as one ODD, represented by the terms "All HW" or "ALLHW," and 9 ODDs from specific highways: I-5, I-10, I-20, I-35, I-40, I-70, I-75, I-80, and I-95 (Figure 1).

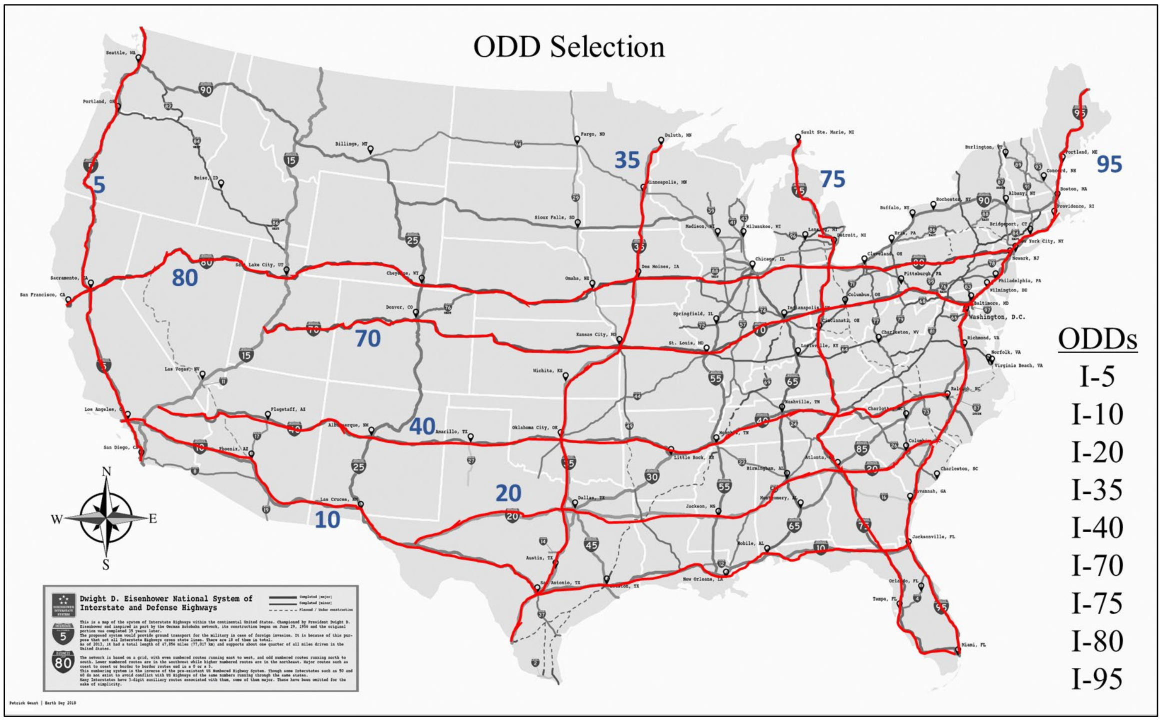

Figure 1. Map. Automated Class 8 tractor-trailer driving performance highways used for geographic map–matching.

2.2.1 Class 8 ODD Framework

When developing the study and selecting ODDs for this project, the research team collected information on factors believed to be important to original equipment manufacturers (OEMs) and ADS technology providers. This information, along with information from other sources (e.g., the American Association of State Highway Transportation Officials [AASHTO]), is summarized in Appendix B.

The variables and gradations were informed by the National Highway Traffic Safety Administration (NHTSA) report, *A Framework for Automated Driving System Testable Cases and Scenarios*.[16] A summary of the final organization of the ODDs is provided in Appendix B. Elements and variables were selected from this framework to be applied to the criteria for defining highway ODDs. The ODD framework identifies near-term and mid-term ODD categories and variables that developers of ADS-equipped CMVs are working to support. This study provided variables in the near-term and some elements of the mid-term ODD levels.

2.2.2 ODD Matching of Continuous Naturalistic Data

The event data included trip-level data, which includes both time and GPS coordinates. This allows the data to be mapped and filtered through naturalistic driving data. The naturalistic data were matched with geographic map data using Navteq (now HERE Technologies) map data. Two parameters were used to constrain calculation of exposure and behavioral rates to the relevant ODD(s). First, interstate or similar roadways accessible only via controlled entrance and exit ramps were used. Second, speed limits had to be greater than or equal to 40 miles per hour.

These parameter filters resulted in approximately 3.1 million miles of collected continuous naturalistic data.

The GPS points from the naturalistic data were matched to the HERE data through unique link IDs, which are small segments of roadway defined by HERE. Each trip was divided into these unique link IDs, the length of which varied from a few meters to hundreds of meters. The length of each road segment bearing a unique link ID is determined by a set of roadway attributes.

One specific focus of this project was CMV performance on interstates. Values from the link ID attributes “Functional Class” and “Controlled Access” combine to define whether a specific link ID is on an interstate highway. The Functional Class variable defines the roadway hierarchy based on the volume of traffic, speed limit, and road access type. Road access type is also defined by the variable Controlled Access, which specifies whether the access to the roadway segment is controlled by entry and exit ramps.

Link IDs also specify the name of the roadway. This served to sort specific interstates into their ODD. Other roadway characteristics, such as speed limit and number of lanes, were used to define more refined ODDs to study naturalistic driving behavior in a more granular way. Heat maps of the continuous collections for map-matching of these roadway characteristics are provided in Appendix C.

2.2.3 Naturalistic Data Event Reduction

Appendix D contains a description of the event data and assumptions, along with the selection, organization, reduction, and quality assurance review performed by the research team, which included the Virginia Tech Transportation Institute and SmartDrive Systems, Inc.

2.3 DRIVING PERFORMANCE BASELINES

The baseline performance estimates were separated into naturalistic crash and near-crash event performance for the lagging baseline, and into naturalistic continuous vehicle maneuvers and driver behaviors for the leading baseline.

2.3.1 Lagging Performance

The event data included enough recorded vehicle miles to establish a safety performance baseline directly in terms of the estimated crash rate for human-operated CMVs in the studied ODD. However, evaluating ADS-equipped CMVs against such a crash rate baseline will require collecting data from a fleet of ADS-equipped CMVs covering hundreds of millions of vehicle miles, which may not be feasible until after market deployment.

A unique feature of the event data is that crash rates may be estimated, both at the general level (e.g., the overall crash rate for all Class 8 trucks in the United States) and within specific highway ODDs. Moreover, it is possible to obtain rates for specific crash types (e.g., rear-end crashes, run-off-road crashes) with the additional SHRP 2 data reduction. The event data may provide more accurate crash rate estimates than traditional crash data based on police reports for the following reasons. First, the driving exposure can be directly measured rather than estimated based on high-level statistics, and exposure is available for specific driving contexts (ODDs).

Second, many crashes are not reported to the police, resulting in underrepresentation of at least lower-severity crashes in police reported data. The data used in this study were collected directly, avoiding problems of reportage.

2.3.1.1 ADS Potential for Crash Reduction

The number of Class 8 CMV crashes identified in a large naturalistic collection offers a precise baseline for ADS-equipped CMVs. However, this work adds a unique dimension by attempting to classify the elements in crashes that may be affected by ADS in the future. This approach incorporated the following steps and assumptions:

- Activities surrounding actual crashes were recorded on a kinematic triggered, ADAS-triggered, or continuously recorded onboard monitoring system within in each truck.
- The crashes were manually reduced post-collection according to the SHRP 2 dictionary[17]
- The identification of driver fault and non-fault were based on the judgement of a trained expert who manually reviewed the epoch surrounding the crash event.[a]
- The classification of crash causation was based on a theory called Crash Trifecta, most recently tested on SHRP 2 data,[18] which sorts crash causation mechanisms into three categories: negative behaviors, inattention, and unexpected events. All unsafe behaviors and selected driver inattention behaviors are considered high risk and likely to be mitigated by ADS.
- Driver at-fault crashes were classified based on the assumption that not all secondary tasks (that is, actions such as checking a cell phone that are not directly related to driving the vehicle) may be applicable to crash causation. The decision to include only particular types of secondary tasks into an at-fault category is based on each task category's level of risk. Odds ratios (ORs) from SHRP 2, which are defined as the relative association of risk between two events, were applied. [19] Tasks with an OR greater than 2.0 were considered high-risk secondary tasks.

The main limitation to this approach is that the actual success of an ADS in reducing incidents will be strongly tied to the individual OEM/ADS developer's object and event detection and response (OEDR) decision-making knowledge of edge cases and sensor array capabilities, in addition to the level of driver/operator takeover functionality available for ADS implementations that assume the presence of human driver/operator and rely on this presence as a final safeguard. In other words, the safety improvements ADS could provide will depend on data about unusual events and associated automated responses, the performance of sensors designed to detect these events, and—for lower levels of ADS—how easily a driver can re-assume control of the vehicle.

The following classification of vehicle events was applied to the analysis.

- ADS-equipped CMVs may have a high impact on these unsafe behaviors:

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[a] Experts were trained in the objective criteria described in SHRP 2 to assign fault for a given crash based on available data.

    - Impairment (drug/alcohol), drowsiness fatigue, emotion (individual ORs all ≥ 3.4)
    - Driver performance error: inexperience with road, driving slowly, blind spot error, improper turn, right-of-way, etc. (individual ORs all ≥ 2.3)
    - Driver momentary judgement error: aggressive driving, speeding, following too closely, intentional signal/sign violation (individual ORs all ≥ 5.3)
- ADS-equipped CMVs may have a high impact on reducing inattention when drivers engage in these secondary tasks (individual ORs all > 2.0):
    - Adjusting/monitoring devices integral to vehicle
    - Adjusting/monitoring other/unknown instrument panel device
    - Cell phone, browsing
    - Cell phone, dialing hand-held
    - Cell phone, dialing hand-held using quick keys
    - Cell phone, holding
    - Cell phone, locating/reaching/ answering
    - Cell phone, other
    - Cell phone, talking/listening, hand-held
    - Cell phone, texting
    - Look back in sleeperberth
    - Looking at an object external to the vehicle
    - Looking at previous crash or incident
    - Moving object in vehicle, Interact
    - Object dropped by driver
    - Object in vehicle, other
    - Other electronic device, interact with
    - Other external distraction
    - Other known secondary task
    - Reaching for food-related or drink-related item
    - Reaching for object, other
    - Reaching for personal body-related item
    - Reading
    - Tablet device, operating
    - Tablet device, other

Unexpected events have only been classified as being present or not in this analysis. Unlike unsafe behaviors and inattention, these events have not been associated with crashes in a systematic manner due to their variety and complexity. Some of the elements and mitigating factors relate to considerations of the ODD. The ADS-equipped CMV's sensor performance and OEDR performance will determine how (and whether) ADS affects safety outcomes related to these unexpected events.

These events were matched with the lagging baseline of crash rates from the naturalistic event data to produce a relative scale of safety impact that ADS-equipped CMVs may have on Class 8 highway operations. Results for this analysis are given in Section 3.9.

2.3.2 Leading Performance

The research team developed algorithms to select defined subsets of the continuous data for highway driving across the "driving performance" categories and attributes. These subsets were isolated into cases, each defined as a particular vehicle motion. Vehicle activity identified in each case does not necessarily connect to a safety related event, but a case could be associated with a number of different events (e.g., a driver could be speeding and deviating from a lane but not involved in a crash or near-crash).

2.4 DATA TOOLS FOR AUTOMATED CLASS 8 TRACTOR-TRAILER PERFORMANCE

Aggregate data has been stored within the data repository and made available to researchers working with FMCSA. Further, a public-use data tool has been made available that provides event rates based on selected parameters. A sample of the parameters is provided in the lagging and leading results sections.

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3. LAGGING PERFORMANCE RESULTS

3.1 NATURALISTIC EVENT DATA DESCRIPTION

Event data for the lagging performance baseline were gathered during data collection time windows initiated by kinematic- and sensor-based triggers. These epochs may represent both crash and near-crash events. The data typically include camera views, kinematic data, and GPS coordinates, in addition to vehicle data obtained from the vehicle network. In addition, the data include video observations that were coded manually. The data cover a 2-year period from August 2016 to August 2018, represent billions of driving miles, and include over a million triggered events. The large number of naturalistically observed crashes potentially allows for establishing performance criteria in terms of crashes.

3.1.1 Fleets, Vehicle Types, and Operating Environments

The event data came from all types of vehicles, with the general constraint that they be operated for cargo-delivery and are part of a company fleet that is a SmartDrive client. Class 8 trucks account for approximately 70 percent of the entire dataset.

SmartDrive's clients include 331 fleets that have at least one Class 8 truck equipped with a SmartDrive data-collection system. These fleets, which include an estimated 10,000 relevant vehicles, provided the data for this study.

3.1.2 Definition of Crashes and Near-Crashes

The definition for crashes follows the definition used in the SHRP 2 crash data reduction protocol: [20]

- **Crash**: Any contact that the subject vehicle has with an object, either moving or fixed, at any speed. Also includes non-premeditated departures of the roadway where at least one tire leaves the paved or intended travel surface of the road. In some cases, crashes were first identified by clients. Events classified as crashes generally undergo further analysis.
    - *Level 1 Most Severe*: Any crash that includes an airbag deployment; any known injury to passengers, pedal cyclist, or pedestrian; a vehicle rollover; or vehicle damage requiring towing.
    - *Level 2 Crash Moderate Severity*: Not a level 1 crash; a minimum of approximately $1,500 worth of damage as estimated from video; or a police-reportable crash.[b]
    - *Level 3 Crash Minor Severity*: Not a level 1 or 2 crash; the vehicle makes physical contact with another object or departs the road but sustains only

[b] It should be noted that these definitions—and this one in particular—diverge from regulatory definitions of crash types. FMCSA criteria for reportable crashes do not use dollar values; they are based on how much damage a vehicle has sustained—specifically, whether it can be driven away from the scene of a crash.

minimal or no damage. This includes most road departures, small animal strikes, all curb and tire strikes potentially in conflict with oncoming traffic, and other curb strikes with an increased risk element (i.e., the crash may have been worse if the curb had not been there).

  - *Level 4 Crash Tire Strike, Low Risk*: Not a level 1, 2, or 3 crash; the tire is struck with little or no risk element (e.g., clipping a curb during a tight turn).

The definition for near-crash is as follows:

- **Near-Crash**: Any circumstance that requires a rapid evasive maneuver by the subject vehicle or any other vehicle, pedestrian, cyclist, or animal to avoid a crash. Near-crashes must meet the following four criteria:
  - *Not a crash*: The vehicle must not make contact with any object, moving or fixed, and the maneuver must not result in a road departure.
  - *Not pre-meditated*: The maneuver performed by the subject must not be pre-meditated. This criterion does not rule out near-crashes caused by unexpected events experienced during a pre-meditated maneuver (e.g., a pre-meditated aggressive lane change resulting in a near-miss with an unseen vehicle in the adjacent lane that requires a rapid evasive maneuver by one of the vehicles).
  - *Evasion required*: An evasive maneuver to avoid a crash was required by either the subject or another vehicle, pedestrian, animal, etc. An evasive maneuver is defined as steering, braking, accelerating, or a combination of control inputs performed to avoid a potential crash.
  - *Rapidity required*: The evasive maneuver must also require rapidity. Rapidity refers to the swiftness of the response required given the amount of time between the beginning of the subject's reaction and the potential impact.

Events classified as near-crashes generally undergo further analysis.

3.2 EXPOSURE RESULTS

Although the naturalistic data are primarily event-based, mileage and hours of driving exposure can both be calculated from continuously recorded trip data. Hours of driving is usually calculated as the time from ignition on to ignition off, which thus includes idling. However, because SmartDrive tracks idling as a discrete trip segment, idling periods may have been excluded from the time exposure measurements. Also, the recorded speed data can be used to include only the time when the vehicle was moving within the relevant speed range. For these reasons, mileage rather than time duration of trip is the preferred measure of exposure. This report represents exposure in terms of miles.

Table 1 contains the VMT and hours driven exposure data from all roadways included in the study, and from the nine highway systems for which map-matching was performed, across the 10 selected ODDs.

Table 1. VMT and hours driven in the lagging performance baseline ODDs.

ODD	VMT	Hours Driven
All Highways	3,441,694,085	56,175,543
I-5	99,105,041	1,768,981
I-10	269,502,657	4,343,198
I-20	236,840,758	3,693,809
I-35	101,004,018	1,640,265
I-40	329,460,656	5,123,954
I-70	157,890,247	2,535,124
I-75	236,029,129	3,744,697
I-80	181,639,244	2,914,588
I-95	156,858,510	2,631,265

3.3 LAGGING BASELINE: CRASH RATES

3.3.1 Vehicle Involvement

All crash rates are calculated per 100 million VMT per ODD. Although multiple crashes for a single vehicle within a short period were concatenated into a single crash, a single vehicle could have been involved in multiple, more widely separated crashes throughout the 2-year period. Table 2 displays the number of unique vehicles across all 3,781 crashes and the 10 ODDs. Of the 3,497 unique vehicles in the complete dataset, 3,225 were involved in only 1 crash, 262 vehicles were involved in 2 crashes, and 10 vehicles were involved in 3 or more crashes.

Table 2. Unique vehicle count by ODD of vehicles involved in crashes.

ODD	Unique Vehicles*
All Highway	3,497
I-5	97
I-10	223
I-20	209
I-35	133
I-40	258
I-70	186

ODD	Unique Vehicles*
I-75	188
I-80	197
I-95	205

*The unique vehicle counts are specific to the ODD. Vehicles may be represented multiple times across ODDs if only one crash was present in each ODD.

3.3.2 Overall Crash Rates

The overall crashes per 100 million VMT by ODD are detailed in Table 3. These crashes include all crashes on primary roads with Class 8 vehicles. A comparison to FMCSA's published crash rates for all roadway types is provided in Section 5.1. The following formula (Equation 1) is used for rate calculations:

Equation 1. Calculation of crash rate by ODD.

$$Crash\ Rate_{ODD} = \frac{Number\ of\ crash\ events\ on\ the\ ODD}{Total\ VMT\ on\ the\ ODD} \times 100\ million$$

Table 3. Overall crash rates per 100 million VMT by ODD.

ODD	VMT	Total Crashes	Overall Crash Rate
All Highways	3,441,694,085	3,781	109.9
I-5	99,105,041	98	98.9
I-10	269,502,657	230	85.3
I-20	236,840,758	216	91.2
I-35	101,004,018	133	131.7
I-40	329,460,656	262	79.5
I-70	157,890,247	189	119.7
I-75	236,029,129	190	80.5
I-80	181,639,244	198	109.0
I-95	156,858,510	214	136.4

3.3.3 Crash Rate Categories

The overall crash rates combine all crash characteristics and provide useful but limited information on crash metrics. This section further details crash rates across several categories and crash related parameters.

3.3.3.1 *Crash Severity*

As defined in Section 3.1.2, crash severity can be categorized into four levels. The crash rates by both crash severity and ODD are presented in Table 4. The ODD with the highest crash rate for each crash severity is identified with bold lettering. The highest crash rate was Police-reportable Crash on I-95. Combinations of categories can be computed by adding them together. The total will be an accurate rate, meaning that any combinations of interest can be calculated this way. For example, adding the rates for "most severe" and "police-reportable" crashes on I-80 would yield a crash rate of 87.0 for those types of crashes.

Table 4. Crash rates per 100 million VMT by crash severities by ODDs

Crash Severity	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
I—Most Severe	2.4	1.0	1.5	0.8	2.0	1.5	4.4	2.1	**5.0**	3.2
II—Police-reportable Crash	81.3	73.7	56.0	61.6	97.0	52.8	91.2	55.9	82.0	**109.0**
III—Minor Crash	23.0	19.2	24.5	27.4	**29.7**	22.8	19.6	18.6	19.8	20.4
IV—Low-risk Tire Strike	3.1	5.0	3.3	1.3	2.0	2.4	**4.4**	3.8	2.2	3.2

3.3.3.2 *Crash Type*

Crash types can be parsed into 11 categories based on the primary crash that occurred. The crash rates by crash type and ODD are presented in Table 5. The highest ODD value from each crash types is identified with bold lettering. The majority of crashes involved an obstacle or object in the roadway, conflict with an animal, or conflict with a vehicle in an adjacent lane. The crash rates have notable differences based on the ODD of interest. Conflicts with an obstacle or object in the roadway were highest on I-35. Conflicts with an animal were highest on I-70. Conflicts with a vehicle in the adjacent lane were highest on I-95.

Table 5. Crash rates per 100 million VMT by crash types by ODDs.

Crash Types	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
Single-vehicle conflict	11.9	6.1	8.2	6.8	15.8	7.6	**21.5**	9.7	13.8	10.8
Conflict with a lead vehicle	11.1	6.1	8.9	11.0	9.9	7.0	7.0	6.8	10.5	**21.7**
Conflict with obstacle/object in roadway	28.4	26.2	27.8	33.4	**33.7**	27.9	24.7	22.5	26.4	29.3
Conflict with animal	17.8	10.1	9.6	10.1	22.8	10.0	**33.6**	5.1	29.7	8.9
Conflict with vehicle in adjacent lane	28.4	40.4	20.4	18.2	37.6	17.0	22.2	25.8	17.1	**58.7**

Crash Types	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
Conflict with merging or weaving vehicle	0.5	**1.0**	0.7	0.4	0.0	0.0	0.0	0.4	0.6	0.6
Conflict with a following vehicle	7.0	5.0	7.4	8.0	7.9	5.8	6.3	**8.5**	3.9	3.2
Conflict with parked vehicle	0.6	0.0	0.0	0.0	0.0	0.6	0.0	**0.8**	0.6	0.0
Conflict with out of control vehicle in roadway	3.7	4.0	1.5	3.0	3.0	2.7	3.2	0.8	**6.1**	3.2
Conflict with pedestrian	0.1	0.0	0.0	**0.4**	1.0	0.3	0.0	0.0	0.0	0.0
Other	0.1	0.0	0.4	0.0	0.0	0.0	0.0	0.0	**0.6**	0.0

3.3.3.3 Inattention Behaviors Preceding Crashes

Inattentive behaviors involve the driver performing a non-driving related activity (a "secondary task"). The crash rates by inattentive behaviors and ODD are presented in Table 6. The highest crash rate from each inattention behavior category is identified with bold lettering. Multiple behaviors may be coded within the same crash. Because of this, adding multiple behaviors to create groups may produce a crash rate higher than the actual value. The crash rates are adjusted for crashes without a driver-facing camera for which coding inattentive behaviors was impossible. The "No Driver Camera" behavior represents the crash rates of vehicles without a driver-facing camera.

Table 6. Crash rates per 100 million VMT by inattention behaviors (adjusted) by ODDs.

Inattention Behaviors	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
No Secondary Tasks (or No Additional Secondary Tasks)	79.0	64.7	59.6	54.9	**109.5**	43.9	77.9	67.2	56.9	108.1
Cell Phone, Dialing hand-held	0.7	0	0.7	0	0	0.5	0	1.4	0	**3.4**
Moving object in vehicle, Interact	0.9	0	1.2	0	0	0	1.1	0.7	**2.0**	1.1
Other non-specific internal eye glance	1.4	0	0.7	0	**5.4**	1.1	1.1	1.4	1.1	2.3

Inattention Behaviors	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
Object in vehicle, other	2.1	0	0.7	0	1.8	2.1	**2.3**	0	1.1	3.4
Other electronic device, Interact with	0.9	1.8	2.0	0	0	**2.7**	1.1	0.7	2.0	0
Cell Phone, Texting	2.5	0	1.2	1.4	3.6	2.7	2.3	**3.7**	1.1	3.4
Smoking cigar/cigarette	5.5	1.8	1.2	7.5	**10.5**	3.2	7.8	6.8	7.0	5.7
CB Radio, Interact	0.5	0	0.7	0	0	0.5	**1.1**	0.7	0	0
Removing/inserting/ adjusting contact lenses or glasses	0.2	0	0.7	0	0	0	0	0	0	**1.1**
Eating without utensils	1.8	0	1.2	0	1.8	1.6	**2.3**	**2.3**	2.0	3.4
Cell phone, Talking/listening, hands-free	5.2	3.6	1.2	6.8	5.4	2.7	2.3	3.7	5.0	**10.2**
Other known secondary task	1.2	0	0	1.4	**1.8**	0.5	0	0	1.1	3.4
Reaching for object, other	0.9	**1.8**	0	0.7	**1.8**	0	1.1	0	0	2.3
Drinking from open container	0.5	0	0	0	0	1.1	**2.3**	1.4	1.1	0
Looking at an object external to the vehicle	3.0	0	0	3.0	3.6	1.6	2.3	1.4	3.0	**8.0**
Biting nails/cuticles	0.5	0	0	**0.7**	0	0.5	0	**0.7**	0	0
Other personal hygiene	0.5	0	0	0.7	0	0.5	0	0.7	0	**2.3**
Cell phone, Talking/listening, hand-held	0.4	0	0	0	0	0	**1.1**	0	0	**1.1**
Passenger in adjacent seat - interaction	0.4	0	0.7	0	0	0	**1.1**	0	0	0
Drinking with lid, no straw	0.4	0	0	0	1.8	0.5	1.1	0	**2.0**	0
Other external distraction	0.4	0	0	0	0	0.5	0	0	0	**2.3**

Inattention Behaviors	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
Adjusting/monitoring other devices integral to vehicle	0.2	0	0	0.7	0	0	0	0	0	**1.1**
Talking/singing, audience unknown	0	0	0	0	**1.8**	0	0	0	0	0
Eating with utensils	0.2	0	0	0	**1.8**	1.1	0	0	0	0
Cell phone, Holding	0.7	0	0	0.7	0	0.5	0	0	1.1	**3.4**
Passenger in rear seat - interaction	0.2	0	0	0	0	0.5	**1.1**	0	0	0
Reading	0.2	0	0	0	0	0	**1.1**	0	0	0
Unknown type (secondary task present)	0.2	0	0	0	0	0	**1.1**	0	0	0
No Driver Camera*	47.6	57.5	43.8	48.1	46.5	40.7	**57.6**	27.5	61.7	43.4

*No Driver Camera is not adjusted.

Several inattention behaviors were excluded from the table due to low crash rates. Behaviors that had a crash rate between 0.0 and 1.1 per 100 million VMT for all ODDs were not included in the table. These behaviors are:

- Adjusting/monitoring radio
- Cell phone, dialing hands-free using voice-activated software
- Pet in vehicle, interact
- Cell phone, dialing hand-held using quick keys
- Looking at previous crash or incident; Cell phone, locating/reaching/ answering
- Cell phone, browsing
- Drinking with lid and straw
- Reaching for personal body-related item
- Cell phone, other.

Inattention behaviors that had a 0.0 crash rate per 100 million VMT for all ODDs were not included in the table and are:

- Tablet device, other
- Look back in sleeper berth

- Reaching for food-related or drink-related item
- Tablet device, operating
- Adjusting/monitoring other/unknown instrument panel device
- Object dropped by driver

3.3.3.4 Negative Driving Behaviors Preceding Crashes

Negative driving behaviors are typically aggressive, inattentive, or erroneous. The crash rates across both negative behavior categories and ODDs are presented in Table 7. The highest crash rate for each negative behavior category is identified with bold lettering. Multiple behaviors may be coded within the same crash. Because of this, adding multiple behaviors to create groups may produce a crash rate higher than the actual value.

Table 7. Crash rates per 100 million VMT by negative behaviors by ODDs.

Negative Behaviors	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
None (or No Additional Driver Behaviors)	37.6	31.3	24.5	26.2	**56.4**	21.2	38.6	31.4	29.2	54.8
Avoiding other vehicle	1.4	0.0	1.1	0.8	1.0	0.9	**1.9**	0.8	1.1	1.3
Cutting in, too close behind other vehicle	2.1	1.0	1.5	3.4	1.0	1.8	1.9	2.1	2.2	**4.5**
Cutting in, too close in front of other vehicle	3.8	1.0	3.7	2.1	**6.9**	2.7	1.9	3.8	3.3	5.7
Delayed or insufficient braking	8.9	4.0	5.6	6.3	**10.9**	8.8	8.9	3.4	8.8	10.2
Did not see other vehicle during lane change or merge	6.6	1.0	5.2	5.9	8.9	4.9	3.2	5.5	3.3	**13.4**
Distracted	6.4	1.0	2.6	3.0	6.9	6.1	7.0	5.1	6.1	**9.6**
Driving in other vehicle's blind zone	0.6	0.0	0.0	0.4	1.0	0.9	0.0	0.0	0.6	**1.9**
Driving slowly: below speed limit	0.8	0.0	0.7	0.8	1.0	0.6	**1.3**	0.4	0.0	0.6

Negative Behaviors	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
Driving without lights or with insufficient lights	3.7	1.0	3.7	5.1	**5.9**	4.2	5.7	1.3	4.4	1.9
Drowsy, sleepy, asleep, fatigued	2.1	2.0	1.9	2.1	4.0	0.6	**4.4**	2.5	0.6	1.3
Exceeded safe speed but not speed limit	2.8	0.0	1.1	2.5	2.0	1.8	**5.7**	4.2	2.8	3.2
Exceeded speed limit	0.9	0.0	**3.0**	1.3	1.0	0.3	1.3	0.0	0.6	0.6
Following too closely	7.6	6.1	6.7	8.0	4.0	6.4	7.6	5.9	5.5	**14.7**
Lane drifting[c]	11.1	5.0	7.8	9.7	14.9	9.4	**15.2**	9.3	14.3	4.5
Other improper or unsafe lane change	1.9	3.0	0.7	0.8	2.0	0.6	**2.5**	1.3	2.8	0.6
Other improper or unsafe merge/exit/weave	0.4	0.0	0.7	**1.7**	0.0	0.0	0.6	0.0	0.0	0.6
Other improper or unsafe passing	2.7	0.0	3.3	1.7	3.0	1.8	0.6	1.3	1.7	**5.7**
Use of cruise control contributed to late braking	0.2	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	**1.3**
Wrong side of road, not overtaking	0.1	0.0	**1.5**	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Several negative behaviors were excluded from the table due to low crash rates. Behaviors that did not have a crash rate greater than 1.0 per 100 million VMT for at least one interstate ODD were excluded from the table. These are:

- Aggressive driving, other

[c] Note that slight deviations from the center of a lane—and under some circumstances, more significant deviations—are not always dangerous behaviors. Circumstances may even require lane deviation to maximize safety, and changes in in-lane position appear to be commonplace on on-ramps, where the usual driving path may not always lie down the center of the lane. But lane drifting's high correlation with crashes suggests that it *can be* a hazardous behavior. It should also be noted that lane drifting can occur due to inattention or while the driver is attentive as those terms are used in this report.

- Other
- Right-of-way error in relation to other vehicle or person, other or unknown cause
- Improper backing, did not see
- Improper backing, other
- Improper turn, cut corner on right turn
- Improper turn, other
- Improper U-turn
- Other sign (e.g., Yield) violation, apparently did not see sign
- Other sign violation
- Right-of-way error in relation to other vehicle or person, apparent decision failure
- Sudden or improper braking
- Sudden or improper stopping
- Aggressive driving, specific, directed menacing actions
- Apparent unfamiliarity with roadway
- Apparent unfamiliarity with vehicle
- Avoiding animal
- Avoiding object
- Failed to signal
- Illegal passing
- Cutting in at safe distance but then decelerating, causing conflict

Behaviors that had a 0.0 crash rate per 100 million VMT for all ODDs were also excluded from the table. They are:

- Improper turn, cut corner on left
- Improper turn, wide left turn
- Other sign (e.g., Yield) violation, intentionally disregarded
- Driving slowly in relation to other traffic: not below speed limit
- Disregarded officer or watchman

3.3.3.5 Unexpected Events Preceding Crashes

Unexpected events can be parsed into 11 categories based on the type of unexpected event that directly related to the crash. The crash rates across both unexpected event category and ODDs are presented in Table 8. The highest crash rate from each unexpected event category is identified with bold lettering. The crash rates are adjusted to account for crashes without a driver-facing camera for coding unexpected events.

Table 8. Crash rates per 100 million VMT by unexpected events (adjusted) by ODDs.

Unexpected Events	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
Animal or pedestrian runs in front of subject vehicle	18.1	10.8	6.6	9.0	28.3	9.2	**32.8**	7.6	16.7	12.5
Debris hits subject vehicle	24.6	16.2	29.1	19.6	28.3	21.1	20.3	20.4	17.7	**36.4**
Second vehicle pulls out in front of the subject vehicle unexpectedly	4.4	0.0	0.7	5.3	**10.6**	1.6	2.3	4.5	2.0	9.1
Second vehicle encroaches into subject's lane	9.5	16.2	7.3	3.8	21.2	1.6	5.6	11.3	4.9	**22.7**
Second vehicle brakes suddenly in front of subject vehicle	4.1	0.0	0.7	3.8	5.3	1.6	2.3	1.5	1.0	**10.2**
Another vehicle cuts in front of subject vehicle	4.9	3.6	4.6	1.5	3.5	2.2	2.3	6.8	3.9	**12.5**
Changes in traffic happen while the Subject is not paying attention	9.1	1.8	4.0	6.0	12.4	10.8	9.0	7.6	5.9	**17.1**
Other vehicle crash occurring around subject vehicle	2.9	0.0	2.6	**5.3**	1.8	0.5	3.4	2.3	2.0	2.3
None	27.8	23.4	15.2	18.8	35.3	16.2	23.7	28.0	23.6	**38.7**

Unexpected Events	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
Other, please specify in additional commentary	4.4	1.8	2.0	3.0	3.5	3.2	**7.9**	3.0	4.9	3.4

Only one unexpected event type had a 0.0 crash rate per 100 million VMT for all ODDs: Motorcycle splitting lanes around subject vehicle.

3.3.3.6 Environmental Categories During Crashes

Environmental categories detail the environmental conditions under which a crash occurred. The cause of the crash may or may not have been related to the environmental condition. The crash percentages detailed in this section are computed based on all crashes and across the total exposure, and therefore direct comparisons between conditions do not account for time driven in certain environmental conditions. The crash percentages across lighting conditions and ODDs are presented in Table 9. The crash percentages across roadway conditions and ODDs are presented in Table 10. The crash percentages across weather conditions and ODDs are presented in Table 11. The highest ODD percentage from each category is identified with bold lettering in the tables.

Table 9. Crash percentages by lighting conditions by ODDs.

Percentage of Crashes	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
Darkness, not lighted	28.1%	21.4%	26.1%	36.1%	32.3%	27.9%	**36.5%**	23.8%	36.3%	15%
Daylight	58.9%	67.3%	62.5%	54.7%	53.3%	62.6%	49.7%	60.6%	51%	**63.6%**
Darkness, lighted	9.7%	8.2%	8.3%	6.9%	9.8%	6.2%	10.6%	14.2%	8.6%	**20.1%**
Dawn	1.9%	1%	1.3%	1.4%	3%	2.3%	1.6%	1%	**2.6%**	0.4%
Dusk	1.3%	**2%**	1.8%	0.9%	1.5%	1.1%	1.6%	0.5%	1.6%	1%

Table 10. Crash percentages by roadway conditions by ODDs.

Percentage of Crashes	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
Dry	93.6%	96%	**96.1%**	95%	94.8%	91.2%	94.2%	93.7%	86.8%	94.9%
Wet	4.6%	4%	3.9%	4.2%	4.5%	**6.5%**	4.3%	6.3%	4.6%	2.8%
Unknown	0.1%	0%	0%	**0.4%**	0%	0%	0%	0%	0%	0%
Snowy	1.2%	0%	0%	0.4%	0.8%	1.9%	1.1%	0%	**5.6%**	1.9%
Muddy	0.4%	0%	0%	0%	0%	0.4%	0%	0%	**2%**	0.4%
Icy	0.1%	0%	0%	0%	0%	0%	0.5%	0%	**1%**	0%

Table 11. Crash percentages by weather conditions by ODDs.

Percentage of Crashes	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
Clear/Partly Cloudy	94.8%	**98%**	95.7%	95%	97%	92.8%	95.7%	95.9%	90.2%	95.8%
Raining	2.6%	2%	3%	**3.7%**	2.3%	3.4%	1.6%	3.1%	1.6%	1.4%
Overcast	0.3%	0%	0.5%	**0.9%**	0.8%	0.4%	0%	0%	0%	0.4%
Mist/Light Rain	0.9%	0%	0.8%	0%	0%	**1.5%**	1.1%	1%	0.5%	1%
Snowing	0.8%	0%	0%	0%	0%	**1.5%**	1.1%	0%	4%	1%
Unknown	0.1%	0%	0%	0.4%	0%	0%	0%	0%	**0.5%**	0%
Wind Gusts	**0.1%**	0%	0%	0%	0%	0%	0%	0%	0%	0%
Snow/Sleet & Fog	0.2%	0%	0%	0%	0%	0.4%	0%	0%	**2.6%**	0%
Rain & Fog	0.1%	0%	0%	0%	0%	0%	0%	0%	0%	**0.4%**
Fog	0.1%	0%	0%	0%	0%	0%	**0.5%**	0%	**0.5%**	0%

3.4 LAGGING BASELINE: NEAR-CRASH RATES

3.4.1 Vehicle Involvement

Throughout the 2-year period, any given single vehicle was likely to have been involved in multiple near-crashes. Table 12 displays the number of unique vehicles across all 16,767 near-crashes and the 10 ODDs. Of the 11,098 unique vehicles in the complete dataset, 7,550 vehicles were involved in only 1 near-crash, 3,458 vehicles were involved in 2 to 5 near-crashes, 82 vehicles were involved in 6 to 10 near-crashes, and 8 vehicles were involved in at least 11 near-crashes.

Table 12. Unique vehicle count by ODD of vehicles involved in near-crashes.

ODD	Unique Vehicles*
All Highway	11,098
I-5	467
I-10	890
I-20	751
I-35	327
I-40	849
I-70	606
I-75	873
I-80	670

ODD	Unique Vehicles*
I-95	995

*The unique vehicle counts are specific to the ODD. Vehicles may be represented multiple times across ODDs if only one near-crash was present in each ODD.

3.4.2 Overall Near-Crash Rates

The overall near-crashes per 100 million VMT by ODD are detailed in Table 13**.** These near-crashes include all recorded near-crashes on primary roads with Class 8 vehicles.

Table 13. Overall near-crash rates per 100 million VMT by ODD.

ODD	VMT	Total Near-Crashes	Overall Near-Crash Rate
All Highways	3,441,694,085	16,767	487.2
I-5	99,105,041	549	554.0
I-10	269,502,657	1,002	371.8
I-20	236,840,758	811	342.4
I-35	101,004,018	357	353.5
I-40	329,460,656	951	288.7
I-70	157,890,247	658	416.7
I-75	236,029,129	982	416.1
I-80	181,639,244	751	413.5
I-95	156,858,510	1,226	781.6

3.4.3 Near-Crash Rate Categories

The overall near-crash rates detail all recorded near-crashes that occurred in Class 8 vehicles on primary roads. This section further details near-crash rates across near-crash types and behavioral observations. Combinations of near-crash categories can be computed by summing them together.

3.4.3.1 Near-Crash Type

Near-crash types are sorted into nine categories. The near-crash rates across type and ODD are presented in Table 14. The highest ODD value from each near-crash type is identified with bold lettering. The majority of near-crashes involved a vehicle in transport (that is, a vehicle in motion other than the subject vehicle) for all ODDs.

Table 14. Near-crash rates per 100 million VMT by near-crash types by ODDs.

Near-Crash Types	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
Near-crash with Animal	13.6	11.1	3.7	5.1	13.9	10.0	**32.3**	2.5	17.6	8.3
Near-crash with Fixed Object	25.8	28.3	17.8	18.2	**29.7**	17.6	26.6	13.1	22.0	25.5
Near-crash with Other Movable Object	52.2	37.3	47.9	55.3	41.6	41.6	43.1	43.2	**63.9**	58.0
Near-crash with Parked Vehicle	2.0	2.0	0.4	0.8	1.0	1.8	1.9	**3.8**	1.1	1.9
Near-crash with Pedalcycle	0.1	0.0	0.4	0.0	**1.0**	0.0	0.0	0.4	0.0	0.0
Near-crash with Pedestrian	0.6	1.0	0.4	0.0	2.0	0.3	0.0	0.4	**2.2**	0.6
Near-crash with Vehicle in Transport	403.3	491.4	309.1	271.9	277.2	224.3	328.1	361.0	313.8	**699.4**

Two near-crash types had a 0.0 near-crash rate per 100 million VMT for all ODDs:

- Near collision with work zone equipment
- Near crash with train

3.4.3.2 Behavioral Observations During Near-Crashes

SmartDrive has a set of driving-related variables that are coded for each crash, near-crash, and behavioral observation. The nine higher-order categories, including vehicle control, speeding, and distraction, are further divided into the full set of coded behaviors displayed in Table 15. The highest near-crash rate from each behavioral observation category is identified with bold lettering.

Table 15. Near-crash rates per 100 million VMT with behavioral observations by ODDs.

Behavioral Observations	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
Beverage	5.3	4.0	3.3	3.4	1.0	3.3	3.8	4.7	3.9	**12.8**
Captured Roadway Incident	4.1	7.1	3.7	1.7	3.0	2.1	5.1	1.7	3.3	**7.7**

Behavioral Observations	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
Competitive Aggressive Driving	1.0	2.0	0.0	1.7	1.0	0.9	0.0	0.0	1.7	**5.1**
Driver Seatbelt Unfastened (≤ 20 mph)	1.9	0.0	0.4	0.4	0.0	0.3	0.6	0.8	1.1	**9.6**
Driver Seatbelt Unfastened (> 20 mph)	10.1	3.0	8.9	5.9	6.9	4.6	4.4	8.9	3.3	**32.5**
Driving with Two Hands Off Wheel	0.5	0.0	0.7	0.4	1.0	0.3	0.0	0.4	1.1	**1.3**
Exceeded Maximum Fleet Speed	0.5	0.0	0.0	0.0	0.0	**1.2**	0.0	0.8	0.6	0.0
Excessive Speeding (> 10 mph Over Limit)	**1.3**	0.0	0.7	0.8	0.0	0.6	1.3	0.4	1.1	**1.3**
Food	4.1	4.0	3.0	1.3	2.0	3.9	1.9	4.2	2.2	**8.3**
Grooming Personal Hygiene	0.7	1.0	1.1	0.4	**2.0**	0.3	0.6	0.4	0.6	0.0
Lane Departure Straddling Lanes	3.2	0.0	**4.1**	3.8	2.0	1.8	3.2	3.4	3.3	2.6
Mobile Phone Talking (Handheld)	0.8	2.0	1.1	0.4	1.0	0.6	0.6	0.4	1.1	0.6
Mobile Phone Talking (Hands Free)	18.1	8.1	14.1	16.0	12.9	10.3	14.6	17.8	13.2	**30.6**
Mobile Phone Texting Dialing	4.8	2.0	3.0	3.0	2.0	4.6	2.5	3.0	6.1	**10.8**
Moderate Speeding (≤ 10 mph Over Limit)	6.5	0.0	3.7	4.2	3.0	3.9	7.0	4.2	9.4	**9.6**
Not Scanning Road Ahead	4.3	**6.1**	4.5	2.1	2.0	2.1	3.8	3.0	3.3	3.2

Behavioral Observations	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
Operating Other Mobile Device	1.5	1.0	1.1	**2.5**	0.0	0.6	0.6	1.3	2.2	1.9
Other Task	4.7	3.0	2.2	3.0	3.0	2.7	5.1	3.8	5.0	**12.1**
Passenger Seatbelt Unfastened	1.0	0.0	1.1	0.8	**2.0**	1.5	0.0	0.8	1.7	3.8
Raised Voice	0.2	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**2.6**
Ran Off Road	5.8	2.0	4.5	6.8	1.0	5.2	5.7	2.5	6.1	**10.2**
Rude Gesture	7.0	9.1	4.5	4.6	9.9	5.8	5.7	4.2	5.5	**11.5**
Smoking	14.0	11.1	8.9	11.0	14.9	7.9	14.6	16.9	14.9	**19.8**
Unsafe Braking	15.1	**24.2**	14.1	9.3	6.9	7.6	12.0	8.0	4.4	21.0
Unsafe Following (≤ 1 second)	18.1	16.1	13.0	13.1	12.9	12.4	22.2	18.2	14.3	**24.9**
Unsafe Following (1.25–2 seconds)	34.2	53.5	28.6	25.8	19.8	24.9	29.8	29.7	23.1	**47.8**
Unsafe Following (2.25–3 seconds)	15.9	16.1	13.0	11.4	14.9	10.0	10.8	12.7	11.0	**21.0**
Unsafe Following (3.25–4 seconds)	6.5	**15.1**	4.1	3.4	3.0	4.6	5.1	5.5	9.9	8.9
Unsafe Lane Change Merging Passing	15.5	13.1	10.4	14.4	11.9	7.9	15.8	**19.5**	13.2	19.1
Unsafe Turning	2.4	0.0	0.4	2.1	1.0	2.1	4.4	1.3	**5.5**	2.6
Yawning	1.1	0.0	0.7	0.0	1.0	1.5	**1.9**	1.7	1.7	1.3

Several behavioral observation types were removed due to low near-crash rates. Behaviors that did not have a crash rate greater than 1.0 per 100 million VMT for at least one interstate ODD were excluded from the table. These are:

- Unattended moving vehicle
- Failure to attempt to stop at light

- Not checking mirrors
- Drowsy falling asleep
- Failure to yield to vehicle(s)
- Crossed median centerline
- Filling out paperwork

Behavioral events that occurred during a near-crash and had a 0.0 near-crash rate per 100 million VMT due to rounding for all ODDs were not included in the table. These are:

- Not scanning intersection
- Unsafe railroad crossing
- Unsafe backing
- Speeding (≤ 5 mph over limit)
- Passenger(s)
- Passing bar signal
- Improper stop at station
- Incomplete stop at light
- Incomplete stop at stop sign
- Curb check jumped curb
- Failure to attempt to stop at stop sign
- Attained extreme speed
- Driving the wrong way off roadway
- Driving the wrong way on roadway

3.5 LAGGING BASELINE: BEHAVIORAL OBSERVATION RATES

The behavioral observation rates are detailed in the following section. All unique vehicles involved in the behavioral events are counted. All behavioral observation event rates are presented per 100 million VMT based on the ODD of interest. Only 78,745 behavioral events were sampled from an estimated 1,159,521 total behavioral events during the 2-year period.

3.5.1 Vehicle Involvement

Table 16 displays the number of unique vehicles across the sampled 78,745 behavioral observation events and the 10 ODDs. A total of 20,299 vehicles were included in the randomly sampled data.

Table 16. Unique vehicle count across all primary roads of behavioral events.

Event Count	Vehicle Count
Vehicles with 1 behavioral event	7,357
Vehicles with 2–5 behavioral events	8,952
Vehicles with 6–10 behavioral events	2,604
Vehicles with 11+ behavioral events	1,386
Total	79,136

3.5.2 Overall Behavioral Observation Rates

The overall sampled behavioral observation events per 100 million VMT by ODD are detailed in Table 17. The highest value is identified with bold lettering. The table includes all behavioral events on primary roads with Class 8 vehicles.

Table 17. Overall behavioral observation rates per 100 million VMT (unadjusted) by ODD.

ODD	Overall Event Rate
All Highway	2,299.4
I-5	2,292.6
I-10	2,099.1
I-20	2,013.2
I-35	1,308.9
I-40	2,261.9
I-70	**2,496.1**
I-75	1,849.4
I-80	2,429.6
I-95	2,174.6

The adjusted behavioral observation event rate per 100 million VMT by ODD is detailed in Table 18. The highest value is identified with bold lettering. The table includes all behavioral events on primary roads generalized to the total population of triggered events.

Table 18. Overall behavioral observation rates per 100 million VMT (adjusted) by ODD.

ODD	Overall Event Rate
All Highway	33,690.4
I-5	33,590.6
I-10	30,755.8
I-20	29,497.4
I-35	19,177.7
I-40	33,141.6
I-70	**36,572.6**
I-75	27,097.1
I-80	35,598.6
I-95	31,862.4

3.5.3 Behavioral Observation Categories

The sampled behavioral observation rates are based on approximately 6 percent of the total observational events collected on Class 8 vehicles on primary roads in a 2-year period. This section further refines behavioral observation rates by behavioral observation type.

3.5.3.1 Behavioral Observation Rates

SmartDrive has a set of driving related variables that are coded for each crash, near-crash, and behavioral observation. The nine higher-order categories, including vehicle control, speeding, and distraction, are further divided into the full set of coded behaviors displayed in Table 19. The highest event rate from each behavior observation category is identified with bold lettering. All observations are adjusted to generalize from the studied sample to the general population of observed behavioral events.

Table 19. Observation event rates per 100 million VMT with behavioral observation types by ODDs.

Behavioral Observation Types	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
Attained Extreme Speed	134	0	299	37	44	**325**	121	93	307	19
Beverage	1,088	961	1,087	934	769	885	1,021	900	936	**1,168**
Captured Roadway Incident	28	15	22	25	15	18	19	19	40	**47**
Competitive Aggressive Driving	7	0	5	0	15	4	0	12	0	**28**

Behavioral Observation Types	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
Curb Check Jumped Curb	1	0	0	0	**15**	0	0	0	0	0
Driver Seatbelt Unfastened (≤ 20 mph)	17	0	11	6	0	0	9	0	8	**75**
Driver Seatbelt Unfastened (> 20 mph)	1,577	902	1,544	1,101	653	1,072	974	1,130	960	**4,063**
Driving with Two Hands off Wheel	99	44	130	80	15	133	111	93	**145**	121
Drowsy Falling Asleep	2	0	0	0	0	4	0	6	**8**	0
Exceeded Maximum Fleet Speed	10,333	2,661	10,488	11,018	3,569	**15,099**	9,391	9,641	14,730	4,577
Excessive Speeding (> 10 mph Over Limit)	286	207	125	266	102	187	**418**	211	194	252
Failure to Attempt to Stop at Light	3	0	**5**	0	0	0	0	0	0	0
Food	771	695	750	656	450	645	752	639	661	**1,018**
Grooming Personal Hygiene	146	192	103	**204**	73	182	176	137	121	149
Incomplete Stop at Stop Sign	8	0	5	0	**29**	0	28	0	0	0
Lane Departure Straddling Lanes	50	44	54	49	44	44	56	31	**105**	56
Mobile Phone Talking - Handheld	113	103	147	155	73	93	84	99	65	**187**
Mobile Phone Talking - Hands Free	3,075	1,907	2,528	2,970	1,610	3,038	3,053	2,682	2,428	**3,335**
Mobile Phone Texting Dialing	453	177	446	470	290	440	455	360	387	**504**
Moderate Speeding (≤ 10 mph Over Limit)	1,365	1,064	968	1,318	1,204	1,121	**1,717**	987	831	1,168
Not Scanning Road Ahead	51	**133**	65	25	0	9	0	19	8	93
Operating Other Mobile Device	136	133	71	111	116	138	111	99	97	**149**
Other Task	397	192	440	402	145	325	**473**	323	347	467
Paperwork	60	30	65	68	29	40	56	81	40	**84**
Passenger Seatbelt Unfastened	171	89	136	**359**	87	147	102	62	105	149
Passenger(s)	0	0	**5**	0	0	0	0	0	0	0

Behavioral Observation Types	All	I-5	I-10	I-20	I-35	I-40	I-70	I-75	I-80	I-95
Raised Voice	2	0	0	0	0	0	0	6	8	**9**
Ran Off Road	10	0	0	6	0	**22**	9	6	16	9
Rude Gesture	126	15	98	56	87	98	130	106	153	**187**
Smoking	2,180	1,109	1,289	1,961	1,190	2,268	2,422	2,049	**2,573**	1,990
Unsafe Braking	324	606	261	322	189	125	260	217	161	**383**
Unsafe Following (1.25–2 seconds)	4,099	4,598	3,229	3,539	2,858	2,940	4,640	2,974	3,348	**4,652**
Unsafe Following (2.25–3 seconds)	2,200	**2,765**	1,702	1,813	1,494	2,077	2,487	1,502	1,920	1,934
Unsafe Following (3.25–4 seconds)	1,042	**1,405**	892	953	769	983	1,039	844	1,154	803
Unsafe Following (≤ 1 second)	8,916	**15,406**	8,432	7,300	5,687	7,569	12,129	7,629	9,470	8,986
Unsafe Lane Change Merging Passing	3,604	**5,219**	3,219	2,827	2,379	2,869	4,621	3,402	3,751	3,540
Unsafe Turning	138	**355**	54	31	44	156	241	31	121	28
Yawning	374	458	419	291	290	320	232	261	266	**495**

Several behavioral observation types were removed due to low event rates. Behaviors that did not have a crash rate greater than 1.0 per 100 million VMT for at least one interstate ODD were excluded from the table. These are:

- Unsafe backing
- Not scanning intersection
- Incomplete stop at light
- Crossed median centerline
- Driving the wrong way on roadway

Behavioral events that occurred during a near-crash and had a 0.0 near-crash rate per 100 million VMT due to rounding for all ODDs were not included in the table. These are:

- Speeding (≤ 5 mph over limit)
- Unattended moving vehicle
- Passing bar signal
- Unsafe railroad crossing
- Not checking mirrors
- Improper stop at station
- Failure to attempt to stop at stop sign

- Failure to yield to vehicle(s)
- Driving the wrong way off roadway.

3.6 LIMITATIONS OF LAGGING PERFORMANCE BASELINE

The data used to create the lagging performance baselines were all generated by drivers participating in a safety program and therefore employed by fleets that chose to implement that program. This means that the data may not be representative of the general driver and fleet populations; the data studied likely represents fleets and drivers with better-than-average safety performance. The resulting baseline may therefore represent a higher safety standard for ADS-equipped CMVs to meet than one calculated from the general driver population.

3.7 PUBLIC-USE DATASET FOR LAGGING PERFORMANCE BASELINE

The results of the lagging performance baseline have been made available in a public pivot table Web tool. The public-use dataset contains event rates calculated based on the number of events across an exposure given a selected ODD. A set of fixed parameters (see Table 20) constrain the included data.

Table 20. Fixed parameters for the public-use data tool.

Fixed Parameter	Parameter Value
Time Period	2016–2018 (2 years)
Country	U.S.
States	48 contiguous
Vehicle Class	Class 8 (> 33,000 lbs)
Road Type	Primary Roads

A set of primary parameters (see Table 21) can be used to define criteria to calculate a specific rate. These parameters are largely independent. The two exceptions are (1) the "All Highways" ODD of all primary roads, which will contain the nine sub-ODDs within its rate calculation, and (2) VMT and hours driven exposure metrics, which are based on a ratio.

Table 21. Primary parameters for the public-use data tool.

Primary Parameters	Selection Options
ODD	All highway, I-5, I-10, I-20, I-35, I-40, I-70, I-75, I-80, or I-95
Event Type	Crash or Near-Crash
Exposure Metric	VMT or Hours Driven

This provides a 10 (ODD) × 2 (Event type) × 2 (Exposure metric) factorial design of largely independent data, for a total of 40 primary parameter options.

Secondary parameters may be selected for any rate calculation within the data tool. The variables within these parameters were reduced using the SHRP 2 data dictionary for crash reduction. The full list of secondary parameters is detailed in Table 22. Secondary parameters consist of the specific crash details and are not independent from one another.

Table 22. Secondary parameters by categories for the public-use data tool for crash rate calculation.

Pre-crash Parameters	Crash Parameters	Post-crash Parameters	Driver-related Parameters	Environmental Parameters	Roadway Parameters
Pre-incident Maneuver	Vehicle 1, 2, 3 Configuration	Post-maneuver Control 1, 2	Driver Behavior(s)	Lighting	Visual Obstructions
Precipitating Event	Event Nature 1, 2	Airbag Deployment	Driver Impairment	Traffic Density	Relation to Junction
Subject Vehicle Lane Occupied	Incident Type 1, 2	Vehicle Rollover	Secondary Task(s)	Weather	Roadway Feature
Unexpected Event	Event Severity 1, 2	-	Secondary Task Outcome	Surface Condition	Contiguous Travel Lanes
Vehicle Contributing Factors	Crash Severity 1, 2	-	Driving Tasks	Construction Zone	Through Travel Lanes
Infrastructure Contributing Factors	Evasive Maneuver 1, 2	-	Driver Seatbelt Use	-	Surface Type

Each secondary parameter contains conditional attributes that define the specific details of the crash within the secondary parameter. The sub-parameter may contain discrete observations or conditional levels within the parameter constraints. These sub-parameters can be used to query data for rate calculations under different conditions, such as conflicts with vehicles and other objects in the roadway:

- Vehicle in Motion Conflict
  - Conflict with a following vehicle
  - Conflict with a lead vehicle
  - Conflict with merging or weaving vehicle
  - Conflict with oncoming traffic
  - Conflict with out-of-control vehicle in roadway
  - Conflict with vehicle in adjacent lane
  - Conflict with vehicle turning across another vehicle path (opposite direction)
  - Conflict with vehicle turning into another vehicle path (opposite direction)
- Static Object Conflict
  - Conflict with animal
  - Conflict with obstacle/object in roadway
  - Conflict with parked vehicle
  - Conflict with pedestrian

Under normal crash rate calculations, all secondary parameters are included until they are queried or excluded.

Figure 2 displays an example of a query. This query was built to examine the crash rate for a distracted driver hitting a vehicle, object/obstacle, or animal in front of the vehicle during nighttime conditions. Three secondary parameters and sub-parameters were used in the query.

Fixed Parameters	
Time Period	2016-2018 (2 years)
Country	USA
States	48 contiguous
Vehicle Class	Class 8 (>33,000 lbs)
Road Type	Primary Roads (S1100)

Primary Parameters	
ODD:	Full ODD
Event Type:	Crash Events
Exposure Metric:	VMT

Secondary Parameters	
Parameter 1:	Event Nature 1
Parameter 2:	Secondary Task(s)
Parameter 3:	Lighting
Parameter 4:	[Select One]
Parameter 5:	[Select One]
Parameter 6:	[Select One]

Sub-Parameters	
Sub-Parameter 1:	[Conflict with a lead vehicle; Conflict with animal; Conflict with obstacle/object in roadway]
Sub-Parameter 2:	Distraction(s)
Sub-Parameter 3:	[Darkness – not lighted; Darkness – lighted]
Sub-Parameter 4:	[Select All]
Sub-Parameter 5:	[Select All]
Sub-Parameter 6:	[Select All]

Event Rate Calculation	
Crash events per 100 million VMT	20.5*

*Sample data, not an accurate event rate

Figure 2. Image. Example query for the public-use data tool.

Near-crash events have fewer secondary parameters than crash events. Only two secondary parameters exist due to the nature of the reduction:

- Near-crash event type
- Behavioral observation(s)

Despite this, combinations of behavioral observations can be queried to provide an event rate for multiple specific behaviors occurring during near-crashes.

3.8 LAGGING BASELINE: DRIVER CLASSIFICATION

Aside from rates by VMT, behavioral observations can be parsed based on driver characteristics to identify typical individual behaviors. Vehicles in the sample were separated into the following levels of crash- and/or near-crash involvement (C/NC-involved):

- Crash involved (C-involved)
- Near-crash involved (NC-involved)
- Crash or near-crash involved (C- or NC-involved)
- Crash and near-crash involved (C- and NC-involved)
- Non-crash and non-near-crash involved (Non-C/NC-involved)

The purpose was to identify behavioral characteristics based on vehicles that had crash or near-crash events and compare those with vehicles that had neither crash- nor near-crash involvement. However, the information provided comes with two caveats.

First, these behavioral observations are based on a triggered event. They are not true baselines recorded at random. These events were determined to not fit the near-crash event definition but were still provided to the vehicle's fleet as part of a score and to give context. This limits generalization to determining the proportion of behaviors that were occurring given a triggered event and not during model driving.

Second, triggered events that included no behavioral events were discarded as part of the vendor's policy with their customers. As such, it was impossible to determine a true proportion of events that contain each behavioral observation type. This limits generalization to determining the proportion of behaviors that were occurring given that there was at least one behavior occurring. The formula used to calculate behavior proportions is shown as Equation 2.

Equation 2. Behavior proportion calculation.

$$\boldsymbol{Behavior\ Proportion_{C/NC}^{i} = \frac{No.\ of\ events\ with\ observation, i, and\ level\ of\ crash - involvement, C/NC}{Total\ events} \times 100}$$

Combined, these caveats suggest that comparisons between crash involved and near-crash involved vehicles are limited to description of which behaviors were present within the characterized category, rather than across categories. These proportions of behaviors during events are detailed in Table 23. The highest proportion of driver behaviors observed in each crash involvement category is identified with bold lettering.

Table 23. Proportions of behavioral observations with levels of C/NC involvement.

Proportion (%) of Behavioral Observations	C-involved	NC-involved	C- or NC-involved	C- & NC-involved	Non-C/NC-involved
Near-crash with Animal	0.00	0.01	0.01	0.00	0.00
Near-crash with Fixed Object	0.04	0.05	0.04	0.06	0.00
Near-crash with Other Movable Object	0.04	0.09	0.08	0.06	0.00
Near-crash with Parked Vehicle	0.01	0.01	0.01	0.02	0.00
Near-crash with Vehicle in Transport	0.48	0.88	0.80	0.81	0.00
Attained Extreme Speed	0.38	0.32	0.33	0.40	0.48
Beverage	3.04	3.13	3.10	3.18	3.38
Captured Roadway Incident	0.11	0.08	0.09	0.08	0.08
Competitive Aggressive Driving	0.05	0.03	0.03	0.08	0.01
Crossed Median Centerline	0.02	0.01	0.00	0.03	0.00
Curb Check Jumped Curb	0.01	0.00	0.00	0.02	0.01
Driver Seatbelt Unfastened (≤ 20 mph)	0.06	0.06	0.05	0.08	0.05
Driver Seatbelt Unfastened (> 20 mph)	5.50	4.84	4.79	6.30	4.56
Driving with Two Hands Off Wheel	0.28	0.28	0.28	0.27	0.31
Drowsy Falling Asleep	0.01	0.01	0.01	0.02	0.01
Exceeded Maximum Fleet Speed	**28.22**	**27.82**	**28.14**	**26.39**	**33.62**
Excessive Speeding (> 10 mph Over Limit)	0.76	0.92	0.90	0.82	0.79

Proportion (%) of Behavioral Observations	C-involved	NC-involved	C- or NC-involved	C- & NC-involved	Non-C/NC-involved
Failure to Attempt to Stop at Light	0.00	0.01	0.01	0.00	0.01
Food	2.32	2.19	2.24	2.06	2.34
Grooming Personal Hygiene	0.47	0.41	0.42	0.46	0.44
Incomplete Stop at Light	0.01	0.00	0.00	0.00	0.00
Incomplete Stop at Stop Sign	0.01	0.01	0.01	0.02	0.04
Lane Departure Straddling Lanes	0.17	0.17	0.18	0.11	0.11
Mobile Phone Talking - Handheld	0.28	0.31	0.31	0.27	0.37
Mobile Phone Talking - Hands Free	9.71	9.25	9.25	10.04	8.99
Mobile Phone Texting Dialing	1.35	1.30	1.32	1.30	1.38
Moderate Speeding (≤ 10 mph Over Limit)	4.14	3.92	3.93	4.20	4.19
Not Scanning Road Ahead	0.16	0.19	0.18	0.21	0.12
Operating Other Mobile Device	0.37	0.45	0.44	0.36	0.36
Other Task	1.14	1.29	1.25	1.30	1.10
Paperwork	0.19	0.19	0.19	0.17	0.16
Passenger Seatbelt Unfastened	0.43	0.29	0.34	0.24	0.71
Raised Voice	0.00	0.01	0.00	0.00	0.01
Ran off Road	0.14	0.03	0.05	0.08	0.00
Rude Gesture	0.52	0.44	0.45	0.54	0.29
Smoking	7.24	6.78	6.81	7.35	6.08
Unsafe Braking	0.84	1.09	1.06	0.89	0.84
Unsafe Following (≤ 1 second)	25.92	27.27	27.22	25.31	25.58

Proportion (%) of Behavioral Observations	C-involved	NC-involved	C- or NC-involved	C- & NC-involved	Non-C/NC-involved
Unsafe Following (1.25–2 seconds)	12.95	12.85	12.81	13.26	11.42
Unsafe Following (2.25–3 seconds)	6.70	6.62	6.60	6.89	6.45
Unsafe Following (3.25–4 seconds)	2.80	2.99	2.98	2.71	3.22
Unsafe Lane Change Merging Passing	10.58	11.42	11.34	10.50	9.94
Unsafe Turning	0.51	0.47	0.47	0.54	0.34
Yawning	1.12	1.07	1.07	1.12	1.15

Note: This breakdown is only for the All Primary Road ODD.

Within each triggered event, it was possible for multiple behavioral observations to be coded simultaneously. This is represented in Table 23 when any level of C/NC-involvement is summed across all behavioral observation types. The number and proportion of events, along with the number of behavioral observations coded within the events and the average number of events per level of C/NC involvement, are described in Table 24.

Table 24. Number of behavioral observations notated per event with levels of C/NC involvement for all highway ODDs.

Number of Behavioral Observations Notated	C-involved	NC-involved	C- or NC-involved	C- & NC-involved	Non-C/NC-involved
1	7,779 (74%)	28,311 (74%)	31,381 (74%)	4,709 (75%)	26,875 (74%)
2	2,328 (22%)	8,599 (23%)	9,587 (23%)	1,340 (21%)	8,302 (23%)
3	322 (3%)	1,114 (3%)	1,241 (3%)	195 (3%)	1,088 (3%)
4	34 (<1%)	96 (<1%)	111 (<1%)	19 (<1%)	97 (<1%)
5	1 (0%)	6 (0%)	6 (0%)	1 (0%)	8 (0%)
Average number of behavior observations	1.29	1.29	1.29	1.28	1.29

Overall, these results show little difference in driving behaviors within and between all levels of C/NC involvement—that is, whether a vehicle was involved in a crash or near-crash was not a strong predictor of how many observed behaviors were present in the associated data. This is likely due to the two previously mentioned caveats, and also may be partially due to the nature of reduction (e.g., business practices may limit what fleets are focused on capturing; and some behaviors are not identified by the vendor among multiple behaviors).

3.9 LAGGING BASELINE: CRASH CAUSATION

The purpose of this analysis is to determine safety performance benchmark values for human-operated CMVs which may be used to assess the safety performance of ADS-equipped CMVs, and to provide estimates on the potential safety improvement of the introduction of ADS-equipped CMVs. Crash rate benchmarks are split out by experimentally assigned fault (At Fault and Not at Fault). The estimated effect of ADS is assessed using the Crash Trifecta model. [21] The Crash Trifecta model, as previously described in section 2.3.1.1 breaks out the crash causation mechanisms into three categories: negative behaviors, inattention, and unexpected events.

A series of crash rate benchmarks was created according to a 2 × 2 × 2 × 2 configuration ({At Fault, Not at Fault} × {Negative Behavior Present, Negative Behavior Absent} × {Inattention Present, Inattention Absent} × {Unexpected Event Present, Unexpected Event Absent}. This created 16 independent crash rates, which can be summed to create aggregate crash rates. These benchmarks are detailed in Table 25.

Table 25. Crash Trifecta crash rates per 100 million VMT benchmarks (adjusted) based on the presence (+) or absence (-) of the mechanism in each crash.

Fault	Negative Behavior	Inattention	Unexpected Event	Crash Rate
At Fault	+	+	+	3.63
At Fault	+	+	-	1.76
At Fault	+	-	+	8.56
At Fault	+	-	-	12.61
At Fault	-	+	+	2.18
At Fault	-	+	-	0.62
At Fault	-	-	+	3.42
At Fault	-	-	-	2.44
Not at fault	+	+	+	0.88
Not at fault	+	+	-	0.21
Not at fault	+	-	+	9.29
Not at fault	+	-	-	1.04
Not at fault	-	+	+	5.03
Not at fault	-	+	-	0.52
Not at fault	-	-	+	49.13
Not at fault	-	-	-	8.66

Identifying the effect that ADS may have on crash rates is challenging due to the numerous confounding and moderating variables on the driver-crash relationship. The influence of each of the Crash Trifecta elements was described in Section 2.3.1.1, and is summarized as follows:

- Unsafe Behavior (assume ADS-equipped CMVs will not emulate unsafe human behaviors by design)
- Inattention (assume ADS-equipped CMV will not emulate human inattention by design)
- Unexpected Events (assume ADS-equipped CMV will not manage applicable events differently than humans in the near term)

Fault assignment is an important factor in estimating the future effect of ADS-equipped CMVs on crash rates; crashes in which the driver is at fault, typically due to driver error, would be most reduced by the introduction of an ADS. But crashes that are the fault of others or of the situation (deemed no fault) are less likely to be mitigated by the introduction of an ADS, because driver input is a smaller factor in the crash event.

A complex relationship for not-at-fault crashes is expected. ADSs may reduce not-at-fault crashes due to the increased monitoring and controlling systems in unusual situations, but crashes may also increase due to the reactions of drivers operating other vehicles. These drivers may have their own expectations based on human operated machinery and may not react appropriately given an ADS controlled system in their environment.

4. LEADING PERFORMANCE RESULTS

4.1 DATA DESCRIPTION

Leading performance results were generated from the continuous naturalistic trip data. The naturalistic data were sourced from six collections over 6 years (2011–17) on cargo-delivery trucks.

Continuous naturalistic data typically include time series of sensor data sampled at a relatively high rate (typically 10–20 Hz) and video data including at least a view of the driver and a view of the road ahead. However, other video views are often included, such as additional in-cab views and cameras covering the vehicle's blind spots.

The continuous (time series) data typically consist of data recorded directly by the data acquisition system (DAS) but also include signals from the vehicle network (primarily the J1939 bus for trucks) and potentially from other external modules. The time series data were mined to automatically extract certain events/behaviors, as described in Section 2.3.2. Given that exposure (e.g., VMT or driving time) can be calculated, this allows for calculations of true rates (or true proportions) for these behaviors/events per VMT or hour of driving time.

4.2 CONTINUOUS NATURALISTIC DATA DESCRIPTION

The FAST DASH, OBMS FOT, and CNTD collections were chosen for application to the analysis because these datasets constitute a relatively homogenous and rich continuous data set, with mainly Class 8 vehicles and highway operations.

4.2.1 Continuous Dataset Description

Five datasets collected by the research team in previous research projects were applied to the analysis across the 10 ODDs. These five collections are summarized below.

FAST DASH 1, 2, and 4: The purpose of the FAST DASH studies, collected between 2010 and 2017, was to conduct independent evaluations of safety technologies aimed at CMV operations. The studies evaluated a blind-spot detection system, an onboard monitoring system (OBMS), and a wearable fatigue monitoring system, respectively. The data collection methodology was similar across the three studies and studied the same fleet. The NextGen DAS was used, and the data include four or five video views and GPS, radar, lane tracking, yaw rate, accelerometer data, and many signals obtained from the vehicle network. One key advantage of the FAST DASH data for the present purposes is that the instrumented truck population was of relatively homogenous types and operation. All vehicles were Class 8 trucks (the majority of the same make and model) and engaged mainly in long-haul operations. FAST DASH 1 and 2 also involved manual validation and reduction of safety-critical events (SCEs) such as crashes, tire strikes, near-crashes, crash-relevant conflicts, and unintended lane departures. No randomly sampled baseline (non-SCE) data were included in these studies. Altogether, the FAST DASH studies involved 56 trucks collecting a total of 2,900,000 miles of data.

OBMS FOT 1 and 2: The OBMS FOT collections were funded by FMCSA and used to evaluate the safety effects of a video-based OBMS. They analyzed the risks associated with driver distraction and fatigue. The analysis used the entire OBMS truck dataset and involved manual validation and reduction of SCEs in addition to sampling and reduction of random baseline data. The data cover 202 trucks in 7 fleets for a total of 2,713,041 miles. The video and sensor data were collected with the NextGen DAS and contain similar variables as the FAST DASH data. The fleets in the dataset were somewhat different than FAST DASH with respect to truck types and operations, with the majority of the fleets focusing on local operations. A key advantage of this dataset for the present purposes is that it includes both SCEs and randomly sampled baselines. Randomly sampled baselines can be used to estimate base rates of manually annotated events/behaviors.

CNTD: The CNTD collection was funded by the Council of Deputy Ministers Responsible for Transportation and Highway Safety (Canada). The Council granted access to the dataset for this study under a data use license (DUL). In contrast to the other studies reviewed here, the CNTD did not evaluate a specific safety system and did not involve any associated experimental interventions (e.g., driving with and without a specific safety system). Two fleets operating in Canada participated, and a total of 943,292 miles of date was collected from 29 vehicles and 25 drivers. The NextGen DAS was used, generating video and sensor data similar to data collected in the FAST DASH and OBMS FOT projects. Like the OBMS FOT collections, the CNTD is less homogeneous than FAST DASH with respect to truck types and operations. Analysis of the Canadian data was limited to application of the continuous data and was analyzed separately. Consequently, the leading performance baseline is separated between 10 ODDs in the United States and 1 ODD in Canada. The rollout of ADS-equipped CMVs onto roadways along northern corridors of freight transportation is anticipated to trail southern corridors due to concerns about winter road conditions. When selecting major interstates throughout the United States, similar reasoning was used to prioritize east-west corridors in the southern tier, such as I-10, over northern east-west corridors, such as I-90. The leading factor baseline results are provided in APPENDIX E.

4.2.2 Data Processing

Data processing included performing quality checks on data from the selected datasets. Generally, each trip is saved in the database in terms of a file ID, which is structured to hold each sensor's data. Ideally, all sensor data for each trip should be available for analysis and reliable. Unfortunately, due to many practical limitations, availability and reliability of these data may be problematic. For example, some of the trips excluded one or more types of sensor data due to problems in the DAS or the sensor itself. In some cases, the sensor may have so much noise that the data are not reliable enough. In other cases, the data require post-processing to eliminate noise.

The first step in quality control was to identify a reliable set of files and sensor data. The research team discovered that the different baseline performance estimates developed in this project do not necessarily need all the sensor data, and each individual baseline could be computed with a single set or a combination of a few sets of sensor data. For example, the speeding baseline depends mostly on the speed variables collected from the J1939 controller area network (CAN) bus or from the GPS data. Following distance information depends mostly on the radar data. Hence, for each baseline estimation category, the research team selected specific sets of file IDs containing reliable data for computing only that particular baseline.

4.2.3 Map Matching

The research team applied existing in-house code to associate the GPS data points from the field collection data with road segments on a digital map, a process called map-matching.[22] HERE Technologies map data are divided into road link IDs, where each link ID is unique and refers to a small unique section of road with some common attributes. This map-matching algorithm helps to identify road characteristics, which in turn helps researchers examine the baseline in a more granular way. GPS data were collected at a frequency of 1 Hz, but could often be noisy and the locations reported may not align with the actual road structure (as shown in Figure 3).

Figure 3. Screenshot. GPS points deviating from the actual roadway.(13)

4.2.4 Radar Processing

The type of radar used in this study is capable of tracking a maximum of eight objects at a time. It tracks the trajectory of each of those objects and returns numerical values for their longitudinal and lateral distance and velocity relative to the host vehicle. This kind of information is especially important in understanding the driver's following behavior and assessing safety and traffic patterns. Radar provides information about the distance to and relative motion of the lead vehicle. While potentially useful in understanding roadway safety, these data are often hard to analyze in their raw form. Consider the example of a host vehicle (vehicle A) following another vehicle (vehicle B). Suddenly, a third vehicle (vehicle C) cuts between them from the left side and moves into the next right lane. During that interval, the radar loses track of vehicle B, and once it reappears, vehicle B is treated as a new object, vehicle D, rather than being recognized as vehicle B. There are also many instances in which the radar reports tracking an object when no object is present; these are referred to as ghost objects. In addition to these problems, the radar data are often contaminated by sensor noise. To avoid anomalies, the research team filtered the radar data with a process developed by Gorman et al. that specifically addresses these issues.[23] This process significantly increases the reliability of the naturalistic radar data. The processing also identifies whether an object is the lead vehicle, whether an object is in the same lane as the host vehicle, and the direction of travel.

4.2.5 Lane Tracking Data

A front camera collects lane tracking data, which is processed by a series of computer vision algorithms to detect the lane lines on the road and the lane offset, which is the relative lateral position of the vehicle inside the lane lines. This method depends on the availability and quality of the video recordings. In several cases, the video data were not available. In other cases, the lanes were not clearly visible, especially at while going through turns at night. Weather conditions also made lane line identification challenging. To address these issues while reporting outcomes, the algorithm developed by VTTI reports a confidence value in which left and right lane detection confidence are reported on a relative scale. Prior experimental validation through video review of lane lines and lane position produced the minimum acceptable confidence value of left/right lane deviation used in this study, which is 26 percent. A filtering algorithm was used to identify only those time segments of a trip with reliable lane information.

4.2.6 Information on Individual Drivers and Fleets

Collectively, data from 244 drivers driving approximately 3.2 million U.S. highway miles across the 6 collections were used to calculate driver performance benchmarks.

4.3 EXPOSURE RESULTS

Computation of the leading exposure values is similar to the lagging exposure computation. Mileage is typically computed by integrating speed over time, from either the GPS speed signal or the vehicle network speed, which may be unavailable on some collection files depending on the availability of the J1939 CAN bus vehicle network.

Each leading feature uses different combinations of kinematic variables. For example, the speed behavior feature depends on the availability of good speed data. However, the lane deviation feature depends on the availability and quality of good lane tracking camera data in addition speed data. This leads to the computation of a separate exposure value for each of the feature categories, as presented in Tables 26, 27, and 28. In Table 26 and all Highway ODD analyses, the terms “All HW” and “ALLHW” refer to all highway data that meet the inclusion criteria for this study, including highways not already listed as a Highway ODD. In Table 28 and for all analyses by Number of Lanes ODD, the notation “1” denotes a single lane and “>6” denotes roadways with more than six lanes. All exposures represent only those miles traveled on a highway with a posted speed limit ≥ 40 mph.

Table 26. Exposure data for highway ODDs.

Highway ODD	Exposure by Speed (miles)	Exposure by Lane Tracking (miles)	Exposure by Radar Data (miles)
I-5	7,484	3,697	3,006
I-10	146,733	84,675	83,525
I-20	43,835	21,609	16,184
I-35	10,237	4,900	3,991
I-40	141,678	69,711	55,883

Highway ODD	Exposure by Speed (miles)	Exposure by Lane Tracking (miles)	Exposure by Radar Data (miles)
I-70	40,349	17,898	21,553
I-75	26,904	12,239	7,581
I-80	49,391	21,993	29,866
I-95	123,119	63,870	37,576
All HW	3,121,751	1,662,094	1,314,506

Table 27. Exposure data for speed limit ODDs.

Speed Limit ODD (mph)	Exposure by Speed (miles)	Exposure by Lane Tracking (miles)	Exposure by Radar Data (miles)
40	2,143	8,940	438
45	8,984	18,334	1,986
50	18,093	12,192	5,592
55	184,089	108,779	53,981
60	302,348	167,195	147,785
65	1,019,740	603,986	369,691
70	1,175,310	591,861	535,912
75	366,299	184,854	176,495
80	11,192	6,623	5,216

Table 28. Exposure data for number of lane ODDs.

Number of Lanes	Exposure by Speed (miles)	Exposure by Lane Tracking (miles)	Exposure by Radar Data (miles)
1	8,915	4,288	2,872
2	2,350,245	1,273,310	1,030,768
3	520,875	263,167	189,568
4	183,077	94,035	67,320
5	47,380	22,395	18,970
6	9,591	4,243	3,836
> 6	1,655	653	648

4.4 LEADING BASELINES

4.4.1 Speed Behavior

Speed behavior is analyzed as the rates of the differences between average speeds and speed limits in miles driven by link ID sections. Link ID segments encode only a single speed limit (for general traffic) and do not reflect different speed limits for CMV and general traffic. Speed behavior is illustrated in Figure 4.

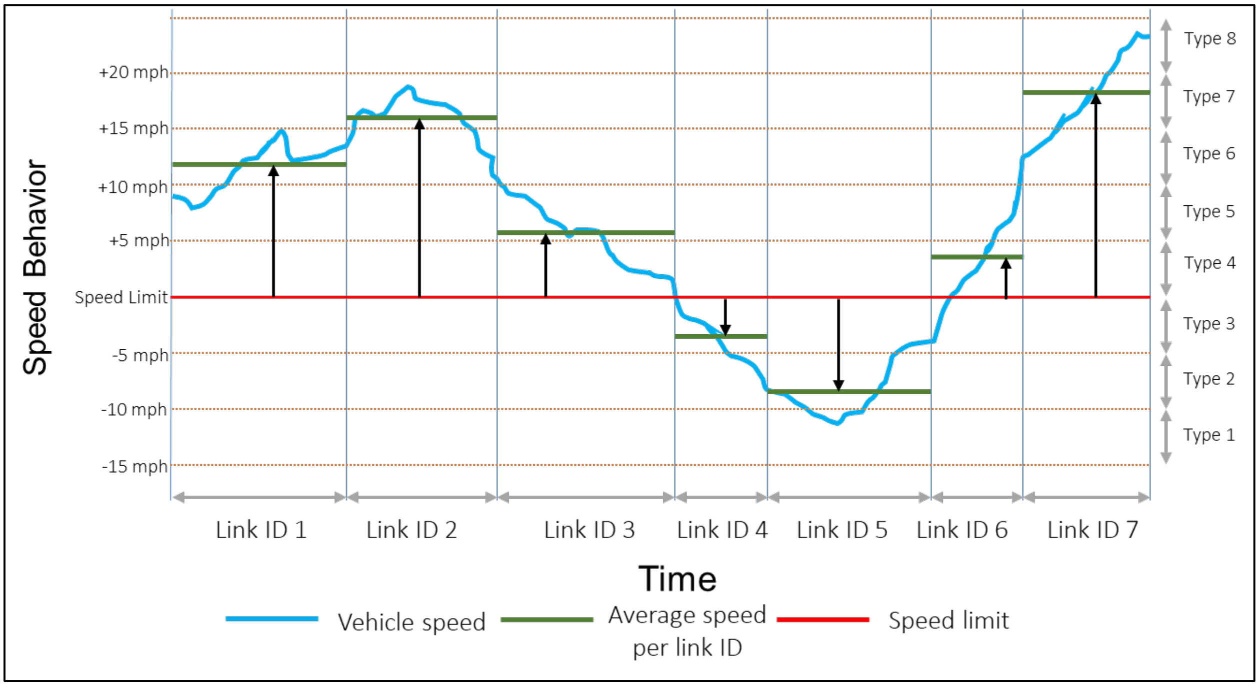

Figure 4. Illustration. Schematic defining the concept of speed behavior.

Speed behavior is categorized in eight types calculated from the vehicle network (J1939) speed signal in each link ID.

- All: speed limit ≥ 40 mph
- Type 1: −15 mph Δ < speed behavior ≤ −10 mph Δ
- Type 2: −10 mph Δ < speed behavior ≤ −5 mph Δ
- Type 3: −5 mph Δ < speed behavior ≤ 0 mph Δ
- Type 4: 0 mph Δ < speed behavior ≤ 5 mph Δ
- Type 5: 5 mph Δ < speed behavior ≤ 10 mph Δ
- Type 6: 10 mph Δ < speed behavior ≤ 15 mph Δ
- Type 7: 15 mph Δ < speed behavior ≤ 20 mph Δ
- Type 8: 20 mph Δ < speed behavior

Where, delta (Δ) denotes the difference between the average speed and roadway speed limit.

4.4.1.1 Speed Behavior by Highway ODDs

Speed behavior types include traveling from 15 mph under the speed limit to 20 or more mph over the speed limit. The rates for each speed behavior are calculated based on number of miles traveled while exhibiting each speed behavior type in each highway ODD and per every 1000 miles. This is done using the following formula, here shown as Equation 3. The terms "All HW" and "ALLHW" refer to all highway data that meet the inclusion criteria for this study, including highways not already listed as a Highway ODD.

Equation 3. Rate of speed behavior per 1000 miles traveled.

$$\boldsymbol{Miles\ Rate^{i}_{Highway\ ODD}} = \frac{\boldsymbol{VMT\ under\ the\ Highway\ ODD\ for\ speed\ behavior\ type\ i}}{\boldsymbol{Total\ VMT\ under\ the\ Highway\ ODD}} \times \mathbf{1000}$$

Highway ODD, as shown in Equation 4, includes all nine sub-ODDs and additional roadway that meets study criteria but does not lie along the nine listed highways:

Equation 4. Highway ODD definition.

$$\boldsymbol{Highway\ ODD} \in \{\text{I-5, I-10, I-20, I-35, I-40, I-70, I-75, I-80, I-95, All HW}\}$$

The exposure VMT for each ODD is reported in Table 26. Speed behavior by all highway ODDs is detailed in Table 29. The highest values from each speed type are identified with bold lettering in the tables. Across all highway ODDs, speed behavior types 2, 3, and 4 had the highest occurrence.

Table 29. Vehicle miles distribution per 1,000 miles exposure in each highway ODD for each type of speed behavior.

Highway ODD	Type 1 (15 to 10 mph below limit)	Type 2 (10 to 5 mph below limit)	Type 3 (5 to 0 mph below limit)	Type 4 (0 to 5 mph above limit)	Type 5 (5 to 10 mph above limit)	Type 6 (10 to 15 mph above limit)	Type 7 (15 to 20 mph above limit)	Type 8 (Over 20 mph above limit)
I-5	**136.5**	357.4	245.3	175.4	31.0	1.4	0.4	0.0
I-10	116.9	329.8	337.4	140.1	28.9	3.8	0.7	0.0
I-20	51.3	218.3	406.6	236.3	49.5	17.5	**2.9**	0.0
I-35	43.4	365.9	**430.7**	118.9	8.0	1.0	0.1	0.0
I-40	24.2	168.0	416.7	**303.5**	58.1	8.6	0.3	0.0
I-70	24.9	322.4	421.7	180.4	27.8	4.6	0.5	0.1
I-75	22.4	357.8	402.1	144.8	38.3	11.9	0.5	0.0
I-80	54.0	**479.9**	316.6	85.4	19.8	3.2	0.7	0.1
I-95	65.4	204.6	324.6	240.1	**111.3**	**23.1**	2.3	**0.5**
All HW	51.6	225.5	370.6	253.0	57.2	11.2	1.2	0.1

4.4.1.2 Speed Behavior by Speed Limit ODDs

The distribution of speed behavior was also analyzed by speed limit ODDs, without distinction for individual highways. The calculation of miles traveled per 1,000 miles for each speed behavior type, in each speed limit ODD, is done using the following formula, shown in Equation 5. The notation “45” indicates a speed limit of 45 mph.

Equation 5. Rate of speed behavior by speed limit per 1000 miles traveled.

$$\boldsymbol{Miles\ Rate^{i}_{Speed\ Limit\ ODD}} = \frac{\boldsymbol{VMT\ under\ the\ Speed\ Limit\ ODD\ for\ behavior\ type\ i}}{\boldsymbol{Total\ VMT\ under\ the\ Speed\ Limit\ ODD}} \times \mathbf{1000}$$

The speed limit ODD includes a series of specific sub-ODDs as shown in Equation 6:

Equation 6. Contents of speed limit ODD.

$$\boldsymbol{Speed\ Limit\ ODD} \in \{\mathbf{40, 45, 50, 55, 60, 65, 70, 75, 80}\}$$

The exposure VMT for each sub-ODD is reported in Table 27. Speed behavior by all speed limit ODDs is detailed in Table 30. Speed limit ODDs showed less consistency than highway ODDs. Speed behavior types 6, 7, and 8 were most frequent in the speed limit ODD of 40 mph. As the speed limit increased, the highest occurring speed behavior type moved to traveling below the speed limit. The highest values from each category are identified with bold lettering in the tables.

Table 30. Distribution of vehicle miles per 1,000 miles exposure in each speed limit ODD for each type of speed behavior.

Speed Limit ODD (mph)	Type 1 (15 to 10 mph below limit)	Type 2 (10 to 5 mph below limit)	Type 3 (5 to 0 mph below limit)	Type 4 (0 to 5 mph above limit)	Type 5 (5 to 10 mph above limit)	Type 6 (10 to 15 mph above limit)	Type 7 (15 to 20 mph above limit)	Type 8 (Over 20 mph above limit)
40	15.9	32.8	92.1	165.2	236.5	**228.1**	**136.9**	**74.1**
45	25.0	65.6	142.2	239.5	229.3	165.7	78.8	21.2
50	16.7	46.5	117.7	239.3	277.0	210.6	51.8	3.7
55	17.6	43.0	119.4	308.2	**334.4**	135.1	8.1	0.1
60	21.9	108.2	300.4	382.9	147.8	9.9	0.5	0.0
65	25.3	82.8	371.3	**449.1**	43.2	1.3	0.0	-
70	60.6	280.1	**507.0**	111.4	15.6	0.0	0.0	-
75	123.7	**666.2**	162.3	2.1	0.2	0.0	-	-
80	**670.9**	236.8	12.2	0.1	0.0	-	-	-

4.4.1.3 Speed Behavior by Number of Lanes

Speed behavior was analyzed by the number of lanes ODDs, without distinction for individual highways. The calculation of miles traveled per 1,000 miles for each speed behavior type, in each number of lanes ODD, is done using the following formula. The notation "1" indicates a single lane and ">6" indicates roadways with more than six lanes. The calculation is shown in Equation 7.

Equation 7. Rate of speed behavior by number of lanes per 1000 miles traveled.

$$\boldsymbol{Miles\ Rate^{i}_{Number\ of\ Lanes\ ODD}} = \frac{\textbf{VMT with SB} - \textbf{type i}\ \boldsymbol{under\ the\ Number\ of\ Lanes\ ODD}}{\boldsymbol{Total\ VMT\ under\ the\ Number\ of\ Lanes\ ODD}} \times \mathbf{1000}$$

The number of lanes ODD includes one to six or more lanes as shown in Equation 8.

Equation 8. Contents of number of lanes ODD.

$$\boldsymbol{Number\ of\ Lanes\ ODD}\ \in \{\mathbf{1, 2, 3, 4, 5, 6, > 6}\}$$

The exposure VMT for each ODD is reported in Table 28. Table 31 shows the distribution of each speeding behavior type by all number of lanes ODDs. The highest values from each category are identified with bold lettering in the tables. A majority of the vehicle miles were observed in type 3 and type 4, with comparatively few miles observed in type 7.

Table 31. Highway miles traveled per 1,000 miles exposure for each type of speeding behavior compared by the available number of lanes.

Number of Lanes ODD	Type 1 (15 to 10 mph below limit)	Type 2 (10 to 5 mph below limit)	Type 3 (5 to 0 mph below limit)	Type 4 (0 to 5 mph above limit)	Type 5 (5 to 10 mph above limit)	Type 6 (10 to 15 mph above limit)	Type 7 (15 to 20 mph above limit)	Type 8 (Over 20 mph above limit)
1	**76.0**	133.6	279.3	309.4	**196.6**	**133.4**	**42.3**	**61.2**
2	57.7	**260.3**	**387.1**	225.7	36.3	4.2	0.9	0.3
3	34.7	136.5	328.4	318.8	111.1	10.2	1.9	1.5
4	28.4	85.3	324.7	380.7	139.5	14.6	2.5	2
5	25.3	76.0	259.2	389.3	156.0	20.9	3.3	0.1
6	33.1	106.7	248.0	340.4	139.5	24.2	5.4	0.2
> 6	37.1	137.7	308.0	**404.5**	92.2	9.3	1.9	0

4.4.2 Lateral Acceleration Left/Right

Lateral acceleration (acceleration left or right) is analyzed by counting the number of cases per 1,000 miles by link ID sections. Lateral acceleration is illustrated in Figure 5.

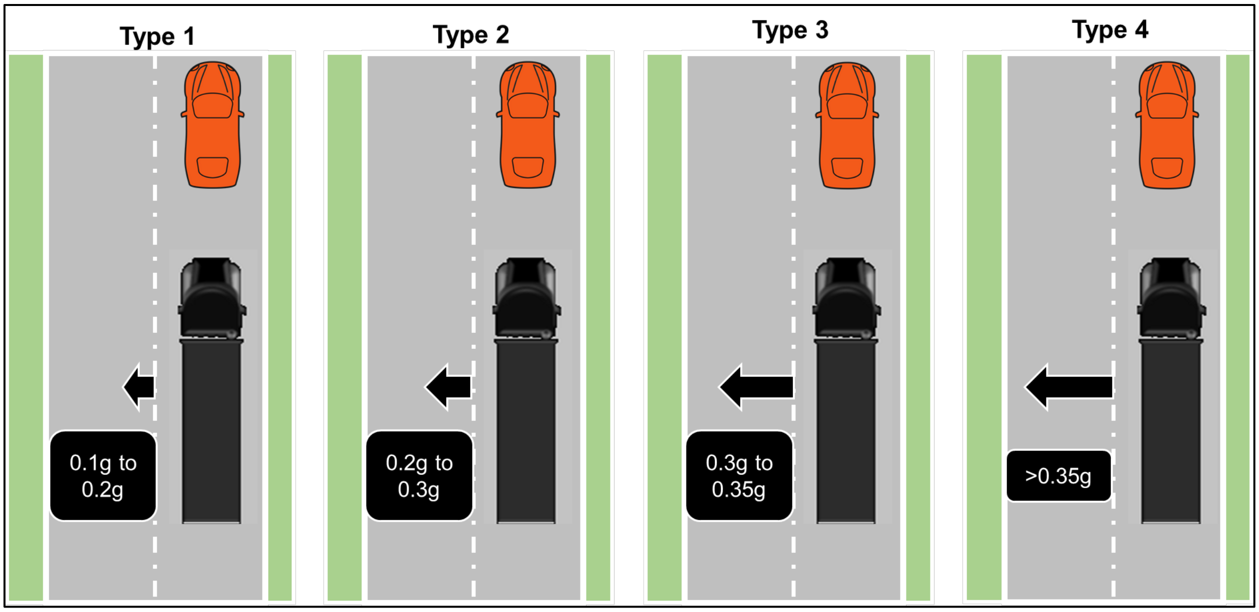

Figure 5. Illustration. Schematic defining the concept of lateral acceleration.

Lateral acceleration is defined by four features calculated from the lateral axis of the accelerometer signal in each link ID, including both left and right (negative/positive) directions.

- All: speed limit ≥ 40 mph, mean acceleration > 0
- Type 1: starting speed ≥ 40 mph, mean acceleration > 0, vehicle lateral acceleration between 0.1 g (inclusive) and 0.2 g
- Type 2: starting speed ≥ 40 mph, mean acceleration > 0, vehicle lateral acceleration between 0.2 g (inclusive) and 0.3 g
- Type 3: starting speed ≥ 40 mph, mean acceleration > 0, vehicle lateral acceleration between 0.3 g (inclusive) and 0.35g
- Type 4: starting speed ≥ 40 mph, mean acceleration > 0, vehicle lateral acceleration greater than 0.35 g (inclusive)

4.4.2.1 Lateral Acceleration by Highway ODDs

The four types of lateral acceleration (LatAccel) behavior range from lateral acceleration of 0.1 g to greater than 0.35 g. Lateral acceleration was measured for both left and right acceleration. The results presented immediately below do not distinguish between left and right acceleration; this distinction is addressed in Section 4.4.2.4. The calculation of event rate per 1,000 miles for each lateral acceleration event type for each highway ODD is done using the following formula as shown in Equation 9. Please note the terms “All HW” and “ALLHW” refer to all highway data that meet the inclusion criteria for this study, including highways not already listed as a Highway ODD.

Equation 9. Event rate for lateral acceleration events per 1000 miles traveled.

$$\boldsymbol{Event\ Rate^{i}_{HW\ ODD}} = \frac{\textbf{LatAccel}\ \boldsymbol{event\ count\ under\ the\ Highway\ ODD\ (type\ i)}}{\boldsymbol{Total\ VMT\ under\ the\ Highway\ ODD}} \times \mathbf{1000}$$

The exposure VMT for each ODD is reported in Table 26. The distribution of lateral acceleration case rates by all highway ODDs is detailed in Table 32. The highest values from each acceleration category are identified with bold lettering in the tables. The ODD for all highways (All HW) had the highest case rate. Lateral acceleration type 1 had the highest case rates in every highway ODD.

Table 32. Rate of lateral acceleration cases per 1,000 miles exposure in each highway ODD for each type of lateral acceleration.

Highway ODD	Type 1 (0.1 g to 0.2 g)	Type 2 (0.2 g to 0.3 g)	Type 3 (0.3 g to 0.35 g)	Type 4 (greater than or equal to 0.35 g)
I-5	307.7	5.8	0.0	0.0
I-10	324.7	11.7	0.4	0.1
I-20	175.9	4.2	0.0	0.0
I-35	150.8	2.2	0.0	0.0
I-40	256.0	9.6	0.1	0.0
I-70	200.6	4.7	0.0	0.0
I-75	195.7	4.4	0.3	0.1
I-80	153.6	4.9	0.0	0.0
I-95	226.3	4.8	0.1	0.0
All HW	**428.4**	**25.3**	**1.0**	**0.3**

4.4.2.2 Lateral Acceleration by Speed Limit ODDs

Lateral acceleration behavior was also compared across different speed limits. The calculation of event rate per 1,000 miles for each lateral acceleration event type, in each speed limit ODD, is done using the following formula, shown as Equation 10. The notation "45" means that 45 mph is the speed limit and so on.

Equation 10. Rate of lateral acceleration events by speed limit ODD per 1000 miles traveled.

$$\boldsymbol{Event\ Rate^{i}_{Speed\ Limit\ ODD}} = \frac{\textbf{LatAccel}\ \boldsymbol{event\ count\ under\ the\ Speed\ Limit\ ODD\ (type\ i)}}{\boldsymbol{Total\ VMT\ under\ the\ Speed\ Limit\ ODD}} \times \mathbf{1000}$$

The exposure VMT for each ODD is reported in Table 27. Table 33 lists the rate of lateral acceleration cases per 1,000 miles traveled for all speed limit ODDs. The highest values from each category are identified with bold lettering. For all speed limit ODDs, lateral acceleration type 1 had the highest rates. Speed limits of 40 mph, 45 mph, and 50 mph had the highest rates of lateral acceleration types 1 and 2. The speed limit of 50 mph had the highest rate of lateral acceleration types 3 and 4.

Table 33. Rate of lateral acceleration cases per 1,000 miles exposure in each speed limit ODD for each type of lateral acceleration behavior.

Speed Limit ODD (mph)	Type 1 (0.1 g to 0.2 g)	Type 2 (0.2 g to 0.3 g)	Type 3 (0.3 g to 0.35 g)	Type 4 (greater than or equal to 0.35 g)
40	**1,423.6**	**329.4**	9.3	1.4
45	1,121.0	180.3	5.5	0.7
50	1,122.7	181.7	**15.3**	**3.9**
55	583.3	32.3	0.5	0.1
60	480.3	27.8	0.5	0.1
65	227.4	4.8	0.1	0.0
70	200.6	4.9	0.1	0.0
75	135.8	4.4	0.1	0.0
80	94.6	1.2	-	-

4.4.2.3 Lateral Acceleration by Number of Lanes

Lateral acceleration behavior was also analyzed by the number of lanes ODDs. The following formula, Equation 11, shows the calculation of event rate per 1,000 miles for each lateral acceleration event type for each number of lanes ODD.

Equation 11. Rate of lateral acceleration events by number of lanes per 1000 miles traveled.

$$\boldsymbol{Case\ Rate^{i}_{Number\ of\ Lanes\ ODD}} = \frac{\textbf{Cases with LA} - \textbf{type i}\ \boldsymbol{under\ the\ Number\ of\ Lanes\ ODD}}{\boldsymbol{Total\ VMT\ under\ the\ Number\ of\ Lanes\ ODD}} \times \mathbf{1000}$$

The exposure VMT for each ODD is reported in Table 28.

Table 34 shows the distribution of different observed lateral acceleration types by different lane number ODDs. The highest values from each category are identified with bold lettering. A majority of the cases observed were type 1.

Table 34. Case rate per 1,000 miles exposure for each type of lateral acceleration compared by the available number of lanes.

Number of Lanes ODD	Type 1 (0.1 g to 0.2 g)	Type 2 (0.2 g to 0.3 g)	Type 3 (0.3 g to 0.35 g)	Type 4 (greater than or equal to 0.35 g)
1	**1,174.8**	**315.3**	**19.3**	**1.91**
2	121.9	8.4	0.4	0.07
3	319.8	18.5	0.9	0.24
4	424.6	19.5	0.7	0.17
5	472.1	13.6	0.2	-
6	563.4	9.7	0.4	-
> 6	641.7	11.5	0.6	-

4.4.2.4 Lateral Acceleration by Direction

Lateral acceleration was measured in both the right and left directions using the same threshold values. Table 35 shows the rate of right lateral acceleration cases per 1,000 miles. Table 36 shows the rate of left lateral acceleration cases per 1,000 miles. Right lateral acceleration case rates were highest in the All HW ODD for all lateral acceleration types. For left lateral acceleration, the highest observed case rates occurred in the I-10 ODD for all lateral acceleration types. The highest values from each category are identified with bold lettering in the tables.

Table 35. Rate of right lateral acceleration cases per 1,000 miles exposure in each highway ODD for each type of right lateral acceleration.

Highway ODD	Type 1 (0.1 g to 0.2 g)	Type 2 (0.2 g to 0.3 g)	Type 3 (0.3 g to 0.35 g)	Type 4 (greater than or equal to 0.35 g)
I-5	171.4	3.9	0.0	0.0
I-10	124.8	4.0	0.1	0.0
I-20	95.4	2.8	0.0	0.0
I-35	71.4	1.5	0.0	0.0
I-40	134.4	6.0	0.1	0.0
I-70	101.7	2.4	0.0	0.0
I-75	74.6	2.0	0.3	0.1
I-80	76.6	2.7	0.0	0.0
I-95	94.5	2.8	0.1	0.0
All HW	**290.2**	**21.2**	**0.9**	**0.2**

Table 36. Rate of left lateral acceleration cases per 1,000 miles exposure in each highway ODD for each type of left lateral acceleration.

Highway ODD	Type 1 (0.1 g to 0.2 g)	Type 2 (0.2 g to 0.3 g)	Type 3 (0.3 g to 0.35 g)	Type 4 (greater than or equal to 0.35 g)
I-5	136.3	1.9	0.0	0.0
I-10	**199.9**	**7.7**	**0.3**	**0.1**
I-20	80.5	1.3	0.0	0.0
I-35	79.4	0.7	0.0	0.0
I-40	121.5	3.6	0.0	0.0
I-70	98.9	2.4	0.0	0.0
I-75	121.1	2.3	0.0	0.0
I-80	77.0	2.3	0.0	0.0
I-95	131.8	2.0	0.0	0.0
All HW	138.3	4.1	0.1	0.0

4.4.3 Longitudinal Deceleration

Longitudinal deceleration is analyzed by counting the number of cases per 1,000 miles by Link ID sections. Longitudinal deceleration is illustrated in Figure 6.

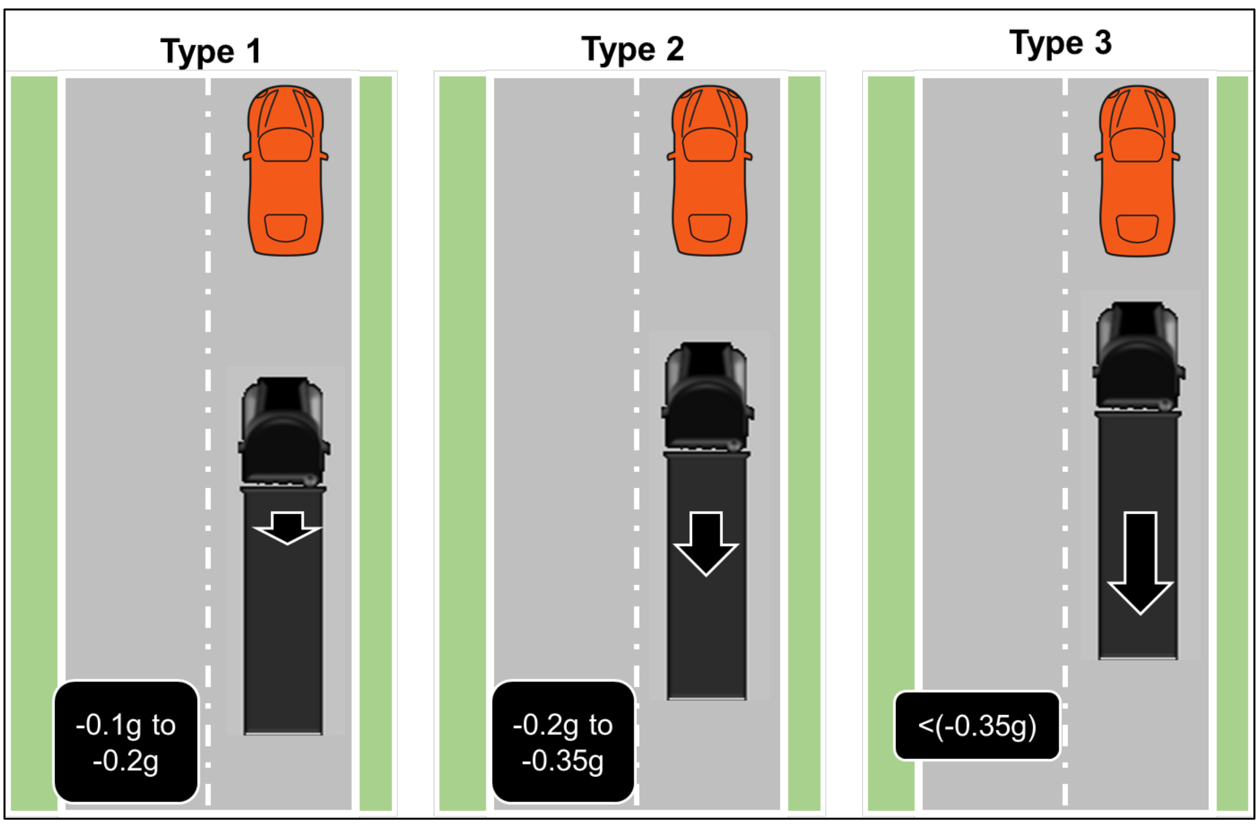

Figure 6. Illustration. Schematic defining the concept of longitudinal deceleration.

Longitudinal deceleration is defined by three features calculated from the longitudinal axis of the accelerometer signal in each link ID.

- All: speed limit ≥ 40 mph, change in speed > 3 mph
- Type 1: starting speed ≥ 40 mph, change in speed > 3 mph, longitudinal deceleration between 0.1 g and 0.2 g
- Type 2: starting speed ≥ 40 mph, change in speed > 3 mph, longitudinal deceleration between 0.2 g and 0.35 g
- Type 3: starting speed ≥ 40 mph, change in speed > 3 mph, longitudinal deceleration greater than or equal to 0.35 g

4.4.3.1 Longitudinal Deceleration by Highway ODDs

Longitudinal deceleration (LonDecel) behavior was classified into three types, with range thresholds from 0.1 g to 0.35 g. The calculation of event rate per 1,000 miles for each longitudinal deceleration event type for each highway ODD was done using the following formula, Equation 12. The terms "All HW" and "ALLHW" refer to all highway data that meet the inclusion criteria for this study, including highways not already listed as a Highway ODD.

Equation 12. Rate of longitudinal deceleration events across highway ODD per 1000 miles traveled.

$$\boldsymbol{Event\ Rate^{i}_{Highway\ ODD}} = \frac{\textbf{LonDecel}\ \boldsymbol{event\ count\ under\ the\ Highway\ ODD\ (type\ i)}}{\boldsymbol{Total\ VMT\ under\ the\ Highway\ ODD}} \times \mathbf{1000}$$

The exposure VMT for each ODD is reported in Table 26. The rate of longitudinal deceleration cases per 1,000 miles for each highway ODD is shown in Table 37. The highest values from each category are identified with bold lettering. Highway ODD I-10 had the highest longitudinal deceleration rates for all three types. For all highway sub-ODDs, type 1 had the highest rates per 1,000 miles.

Table 37. Rate of longitudinal deceleration cases per 1,000 miles exposure in each highway ODD for each type of longitudinal deceleration.

Highway ODD	Type 1 (0.1 g to 0.2 g)	Type 2 (0.2 g to 0.35 g)	Type 3 (greater than or equal to 0.35 g)
I-5	49.8	10.6	0.1
I-10	**54.1**	**10.7**	**0.4**
I-20	19.8	2.6	0.1
I-35	31.5	6.7	0.0
I-40	26.8	3.5	0.1
I-70	20.1	2.6	0.2
I-75	22.3	3.5	0.2
I-80	16.5	1.9	0.1
I-95	38.2	5.5	0.2
All HW	36.3	5.0	0.2

4.4.3.2 Longitudinal Deceleration by Speed Limit ODDs

Longitudinal deceleration behavior was also calculated for speed limit ODDs. The calculation of event rate per 1,000 miles for each longitudinal deceleration event type in each speed limit ODD was done using the following formula, Equation 13.

Equation 13. Rate of longitudinal deceleration events by speed limit ODD per 1000 miles traveled.

$$\boldsymbol{Event\ Rate^{i}_{Speed\ Limit\ ODD}} = \frac{\textbf{LonDecel}\ \boldsymbol{event\ count\ under\ the\ Speed\ Limit\ ODD\ (type\ i)}}{\boldsymbol{Total\ VMT\ under\ the\ Speed\ Limit\ ODD}} \times \mathbf{1000}$$

The exposure VMT for each ODD is reported in Table 27. The rate of longitudinal deceleration cases per 1,000 miles for each speed limit ODD is shown in Table 38. The highest values from each category are identified with bold lettering. Longitudinal deceleration type 1 and type 2 had the highest frequency for the 40 mph speed limit. Longitudinal deceleration type 3 had the highest frequency for the 50 mph speed limit.

Table 38. Rate of longitudinal deceleration cases per 1,000 miles exposure in each speed limit ODD for each type of longitudinal deceleration.

Speed Limit ODD (mph)	Type 1 (0.1 g to 0.2 g)	Type 2 (0.2 g to 0.35 g)	Type 3 (greater than or equal to 0.35 g)
40	**580.9**	**75.1**	0.5
45	236.0	26.6	0.7
50	221.0	43.6	**1.2**
55	105.9	14.2	0.6
60	66.3	11.6	0.5
65	35.0	4.5	0.2
70	21.6	2.7	0.1
75	9.9	1.1	0.1
80	5.5	0.7	-

4.4.3.3 Longitudinal Deceleration by Number of Lanes

The following formula, Equation 14, shows the calculation of event rate per 1,000 miles for each longitudinal deceleration event type for each number of lanes ODD.

Equation 14. Rate of longitudinal deceleration events by number of lanes ODD per 1000 miles traveled

$$\boldsymbol{Case\ Rate^{i}_{Lane\ ODD}} = \frac{\textbf{Cases of LD} - \textbf{type i}\ \boldsymbol{under\ the\ Lane\ ODD}}{\boldsymbol{Total\ VMT\ under\ the\ Lane\ ODD}} \times \mathbf{1000}$$

The exposure VMT for each ODD is reported in Table 28. Table 39 shows the distribution of different longitudinal deceleration types by different lane number ODDs. The highest values from each category are identified with bold lettering in the tables. Once again, the highest case rates were observed in type 1.

Table 39. Case rate per 1,000 miles exposure for each type of longitudinal deceleration compared by the available number of lanes.

Number of Lanes ODD	Type 1 (0.1 g to 0.2 g)	Type 2 (0.2 g to 0.35 g)	Type 3 (greater than or equal to 0.35 g)
1	**1,119.6**	**224.2**	**2.6**
2	29.0	4.5	0.2
3	71.5	17.5	0.7
4	93.7	20.3	0.9
5	118.3	22.8	2.3
6	139.6	31.9	1.8
> 6	153.5	46.5	1.8

4.4.4 Following Distance

Following distance is measured here as headway, which is the distance between the subject and lead vehicles divided by vehicle speed and can be measured in terms of seconds. Following distance is analyzed as the rates of miles driven by Link ID sections. Following distance is illustrated in Figure 7.

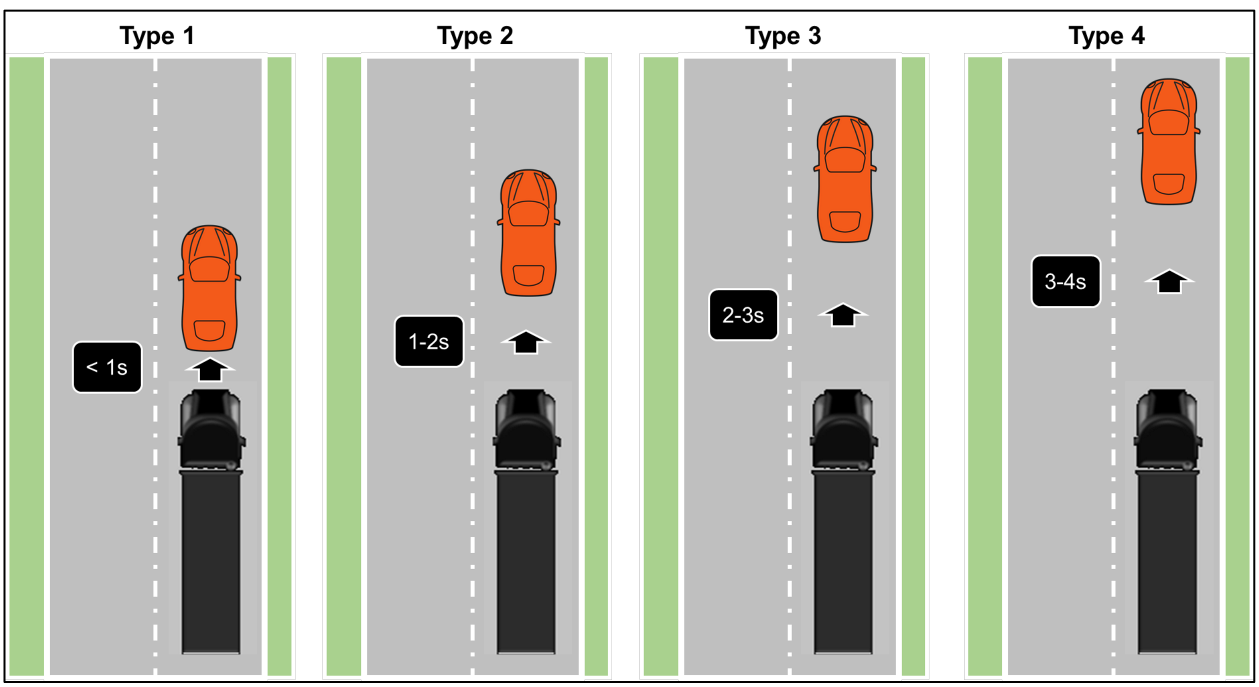

Figure 7. Illustration. Schematic defining the concept of following distance headways.

Following distance is defined by four features calculated from the radar signal in each link ID and a minimum of 40 mph. This study examines following behaviors sustained for at least 3 minutes. This constraint creates a better performance baseline for platooning operations, in which vehicles remain in formation for relatively long periods.

- All: speed limit ≥ 40 mph, following lead vehicle for at least 3 minutes
- Type 1: lead vehicle median headway less than 1 second
- Type 2: lead vehicle headway between 1 and 2 seconds
- Type 3: lead vehicle headway between 2 and 3 seconds
- Type 4: lead vehicle headway between 3 and 4 seconds

4.4.4.1 Following Distance by Highway ODDs

Because following distance calculations rely on radar data, files needed valid, available radar data to be scanned for following distance cases. Because not all files had valid, available radar data, to calculate exposure for following distance, all epochs that met the analysis criteria (speed limit of 40 mph or greater, on highway) were checked for available radar data and then included in the calculation of total distance traveled. The exposure data for following distance for all highway ODDs are presented in Table 40. The terms "All HW" and "ALLHW" refer to all highway data that meet the inclusion criteria for this study, including highways not already listed as a Highway ODD.

Table 40. Highway ODD exposure calculated as total distance traveled in miles for epochs with radar data available.

Highway ODD	Total Distance Traveled in Miles
I-5	3,006.2
I-10	83,525.0
I-20	16,184.3
I-35	3,991.4
I-40	55,883.2
I-70	21,553.2
I-75	7,581.0
I-80	29,865.9
I-95	37,575.6
All HW	1,314,506.1

The calculation of miles traveled per 1,000 miles for each following distance (FD) type in each highway ODD used the following formula, Equation 15.

Equation 15. Rate of following distance behaviors in miles traveled during each behavior per 1000 miles traveled total.

$$\boldsymbol{Miles\ Rate^{i}_{Highway\ ODD}} = \frac{\textbf{VMT with FD} - \textbf{type i}\ \boldsymbol{under\ the\ Highway\ ODD}}{\boldsymbol{Total\ VMT\ under\ the\ Highway\ ODD}} \times \mathbf{1000}$$

The total VMT for all highway ODDs is presented in Table 40. Following distance behavior was classified into four types, ranging from having a very short lead vehicle headway (i.e., less than 1 second) to a long lead vehicle headway of between 3 and 4 seconds. The distance traveled in following distance types per 1,000 miles for each highway ODD is shown in Table 41. The highest values from each category are identified with bold lettering in the tables. For all four types, the highest following distance rate was observed for Highway ODD I-5. Following distance type 2 had the highest rates in all highway ODDs.

Table 41. Highway miles traveled in following distance types per 1,000 miles exposure in each highway ODD for each type of following distance.

Highway ODD	Type 1 (headway less than 1 second)	Type 2 (headway 1 to 2 seconds)	Type 3 (headway 2 to 3 seconds)	Type 4 (headway 3 to 4 seconds)
I-5	0.7	**5.6**	1.6	0.2
I-10	0.1	2.3	3.0	**0.6**
I-20	0.3	3.2	1.2	0.2
I-35	0.1	1.6	0.9	0.2
I-40	0.5	2.5	1.7	0.2
I-70	0.3	2.9	2.8	0.1
I-75	0.1	3.5	2.1	0.4
I-80	**0.9**	3.5	2.8	0.3
I-95	0.7	2.7	2.8	0.1
All HW	0.6	4.4	**3.4**	0.6

4.4.4.2 Following Distance by Speed Limit ODDs

To determine the exposure values for following distance calculations by speed limit ODDs, the same epochs that met the analysis criteria (speed limit of 40 mph or greater, on highway) and had available radar data in the highway ODD analysis were included in the calculation of total distance traveled by speed limit ODD. The exposure data for following distance for all speed limit ODDs are presented in Table 42.

Table 42. Speed limit ODD exposure calculated as total distance traveled in miles for epochs with radar data available.

Speed Limit ODD (mph)	Total Distance Traveled in Miles
40	438.4
45	1,985.9
50	5,593.0
55	53,991.4
60	147,843.2
65	369,911.9
70	536,139.5
75	176,494.6

Speed Limit ODD (mph)	Total Distance Traveled in Miles
80	5,215.8

The following formula shows the method of calculating miles traveled per 1,000 miles for each following distance type in each speed limit ODD.

Equation 16. Rate of following distance behaviors in miles traveled during each behavior per 1000 miles traveled in each speed limit ODD.

$$\boldsymbol{Miles\ Rate^{i}_{Speed\ Limit\ ODD}} = \frac{\textbf{VMT with FD} - \textbf{type i}\ \boldsymbol{under\ the\ Speed\ Limit\ ODD}}{\boldsymbol{Total\ VMT\ under\ the\ Speed\ Limit\ ODD}} \times \mathbf{1000}$$

The total VMT for all speed limit ODDs is presented in Table 42. The highway miles traveled per 1,000 miles for each speed limit ODD and following distance type is listed in Table 43. The highest values from each category are identified with bold lettering. Following distance types 1 and 2 had the highest highway miles traveled per 1,000 miles for the speed limit of 55 mph. Following distance type 3 had the highest highway miles traveled for the speed limit of 60 mph. Following distance type 4 had the highest highway miles traveled for the speed limit of 50 mph.

Table 43. Highway miles traveled per 1,000 miles exposure in each speed limit ODD for each type of following distance.

Speed Limit ODD (mph)	Type 1 (headway less than 1 second)	Type 2 (headway 1 to 2 seconds)	Type 3 (headway 2 to 3 seconds)	Type 4 (headway 3 to 4 seconds)
40	-	1.8	1.6	2.6
45	-	2.2	1.2	0.8
50	0.2	2.0	2.3	**6.3**
55	**2.3**	**6.8**	3.8	3.3
60	0.6	4.3	**4.7**	1.1
65	0.7	4.7	3.2	1.0
70	0.4	4.5	3.6	0.1
75	0.3	2.6	2.2	-
80	-	0.2	2.0	-

4.4.4.3 Following Distance by Number of Lanes

To determine the exposure values for following distance calculations by lane number ODDs, the same epochs that met the analysis criteria (speed limit of 40 mph or greater, on highway) and had available radar data in the highway ODD analysis were included in the calculation of total highway miles traveled by lane number ODD. The exposure data for following distance for all lane number ODDs is presented in Table 44. The notation “1” denotes a single lane and “> 6” denotes roadways with more than six lanes.

Table 44. Number of lanes ODD exposure calculated as total highway miles traveled for epochs with radar data available.

Number of Lanes ODD	Total Highway Miles Traveled
1	2,871.9
2	1,030,768.4
3	189,568.2
4	67,319.8
5	18,970.0
6	3,836.3
>6	648.2

The following formula, Equation 17, shows the calculation of miles traveled per 1,000 miles for each following distance type in each number of lanes ODD.

Equation 17. Rate of following distance behaviors in miles traveled during each behavior per 1000 miles traveled in each number of lanes ODD.

$$\boldsymbol{Miles\ Rate^{i}_{Number\ of\ Lanes\ ODD}} = \frac{\textbf{VMT with FD} - \textbf{type i}\ \boldsymbol{under\ the\ Number\ of\ Lanes\ ODD}}{\boldsymbol{Total\ VMT\ under\ the\ Number\ of\ Lanes\ ODD}} \times \mathbf{1000}$$

The total VMT for each ODD is reported in Table 44. Table 45 shows the distribution of different following distance types by different number of lanes ODDs. The highest values from each category are identified with bold lettering. The highest rate of miles traveled on all highways occurred in six lanes under type 2 following distances.

Table 45. Vehicle mile distribution per 1,000 miles exposure for each type of following distance compared by the available number of lanes.

Number of Lanes ODD	Type 1 (headway less than 1 second)	Type 2 (headway 1 to 2 seconds)	Type 3 (headway 2 to 3 seconds)	Type 4 (headway 3 to 4 seconds)
1	3.3	19.2	5.1	**1.5**
2	1.2	10.7	6.9	0.8
3	2.6	15.3	7.0	0.7
4	4.2	19.0	6.7	0.9
5	3.4	20.0	6.5	0.9
6	**4.3**	**21.3**	**11.1**	1.4
> 6	1.7	16.4	5.9	0.1

4.4.5 Lane Deviation

Lane deviation is measured by the lateral distance between the middle of the lane and the middle line of the truck. Lane deviation is analyzed as the rates of miles driven across link ID sections. Figure 8 illustrates lane deviation.

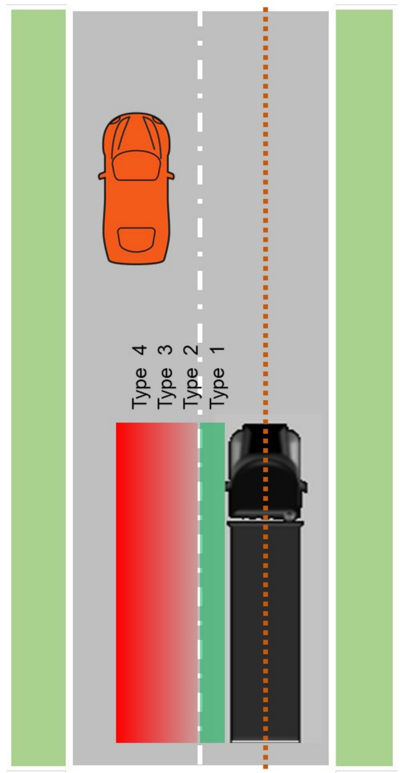

Figure 8. Illustration. Schematic defining the concept of lane deviation.

Lane deviation is defined by four features calculated from the lane offset signal in each link ID.

- All: speed limit ≥ 40 mph
- Type 1, acceptable: deviation 0–21 inches, tires on both sides are inside the lane[d]
- Type 2, violation: deviation 21–33 inches, one tire is 0–12 inches outside the lane
- Type 3, violation: deviation 33–45 inches, one tire is 12–24 inches outside the lane
- Type 4, violation: deviation greater than 45 inches, one tire is more than 24 inches outside the lane

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[d] Note that the descriptions of tire position relative to lane markings are explanatory and inferred from the data, not directly observed. Measures of deviation from the centerline were observed; descriptions of position relative to lane markings are inferred based on the typical width of semi tractor and a lane width of 12 feet. This caveat applies to all included accounts of lane deviation.

4.4.5.1 Lane Deviation by Highway ODDs

The calculation of miles traveled during each lane deviation (LD) type per 1,000 miles in each highway ODD used the following formula, Equation 18.

Equation 18. Rate of land deviations by type in miles traveled during each deviation per 1000 miles traveled in each ODD.

$$\boldsymbol{Miles\ Rate^{i}_{Highway\ ODD}} = \frac{\textbf{VMT with LD} - \textbf{type i}\ \boldsymbol{under\ the\ Highway\ ODD}}{\boldsymbol{Total\ VMT\ under\ the\ Highway\ ODD}} \times \mathbf{1000}$$

The exposure VMT for each ODD is reported in Table 26. Table 46 shows the distribution of different lane deviation types observed in different highway ODDs. The highest values from each category are identified with bold lettering. As expected, a majority of the miles traveled on all the highways were type 1, in which the truck was inside the lane markings.

Table 46. Vehicle mile distribution per 1,000 miles exposure for each type of lane deviation by 10 highway ODDS.

Highway ODD	Type 1 (0-21 inches, inside lane)	Type 2 (21-33 inches, outside lane)	Type 3 (33-45 inches, outside lane)	Type 4 (greater than 45 inches, outside lane)
I-5	958.7	35.2	3.3	2.9
I-10	971.5	25.1	1.9	1.5
I-20	966.8	29.0	2.3	1.9
I-35	**977.1**	19.5	1.8	1.6
I-40	962.9	32.2	2.7	2.2
I-70	972.5	22.2	1.9	3.4
I-75	944.1	**48.8**	**4.9**	2.2
I-80	964.5	29.3	2.7	**3.5**
I-95	944.2	**48.8**	4.1	3.0
All HW	953.1	39.5	4.3	3.1

4.4.5.2 Lane Deviation by Speed Limit ODDs

The following formula, Equation 19, shows the calculation of miles traveled per 1,000 miles for each lane deviation type and speed limit ODD.

Equation 19. Rate of lane deviation in miles traveled during deviation type per 1000 miles traveled in each speed limit ODD.

$$\boldsymbol{Miles\ Rate^{i}_{Speed\ ODD}} = \frac{\textbf{VMT with LD} - \textbf{type i}\ \boldsymbol{under\ the\ Speed\ ODD}}{\boldsymbol{Total\ VMT\ under\ the\ ODD}} \times \mathbf{1000}$$

The exposure VMT for each ODD is reported in Table 27. Table 47 shows the distribution of lane deviation types observed in different highway ODDs. As expected, a majority of the miles traveled on all highways were type 1, in which the truck was inside the lane markings.

Table 47. Vehicle mile distribution per 1,000 miles exposure for each type of lane deviation by nine speed limit ODDs.

Speed Limit ODD (mph)	Type 1 (0-21 inches, inside lane)	Type 2 (21-33 inches, outside lane)	Type 3 (33-45 inches, outside lane)	Type 4 (greater than 45 inches, outside lane)
40	960.0	33.4	4.0	2.6
45	920.3	**56.7**	**12.6**	**10.3**
50	946.1	41.5	8.1	4.3
55	954.6	36.8	5.0	3.6
60	968.7	25.8	2.8	2.7
65	944.2	46.4	5.9	3.6
70	957.6	36.9	3.0	2.6
75	959.0	35.2	3.0	2.8
80	**982.1**	15.2	1.2	1.5

Lane Deviation by Number of Lanes

The following formula, Equation 20, shows the calculation of miles traveled per 1,000 miles for each lane deviation (LD) type and number of lanes ODD.

Equation 20. Rate of lane deviation by miles traveled during each deviation type per 1000 miles of each lane number ODD.

$$\boldsymbol{Miles\ Rate^{i}_{Number\ of\ Lanes\ ODD}} = \frac{\textbf{VMT with LD} - \textbf{type i}\ \boldsymbol{under\ the\ Number\ of\ Lanes\ ODD}}{\boldsymbol{Total\ VMT\ under\ the\ Number\ of\ Lanes\ ODD}} \times \mathbf{1000}$$

The exposure VMT for each ODD is reported in Table 28. Table 48 shows the distribution of different lane deviation types observed in different highway ODDs. The highest values from each category are identified with bold lettering. As anticipated, the majority of the miles traveled on all highways were type 1, in which the truck was inside the lane markings.

Table 48. Vehicle mile distribution per 1,000 miles exposure for each type of lane deviation compared by the available number of lanes.

Number of Lanes ODD	Type 1 (0-21 inches, inside lane)	Type 2 (21-33 inches, outside lane)	Type 3 (33-45 inches, outside lane)	Type 4 (greater than 45 inches, outside lane)
1	780.8	**121.0**	**53.2**	**45.0**
2	950.1	42.3	4.4	3.2
3	962.2	31.8	3.5	2.5
4	970.2	24.8	2.8	2.2
5	978.0	17.4	2.1	2.5

Number of Lanes ODD	Type 1 (0-21 inches, inside lane)	Type 2 (21-33 inches, outside lane)	Type 3 (33-45 inches, outside lane)	Type 4 (greater than 45 inches, outside lane)
6	**984.2**	11.0	2.1	2.7
> 6	973.9	16.9	4.6	4.7

4.4.6 Lane Stability

Lane stability is analyzed as statistical measures of average deviation from lane center, variance in lane position, and peak distance from lane center across link ID sections. Lane stability is illustrated in Figure 9.

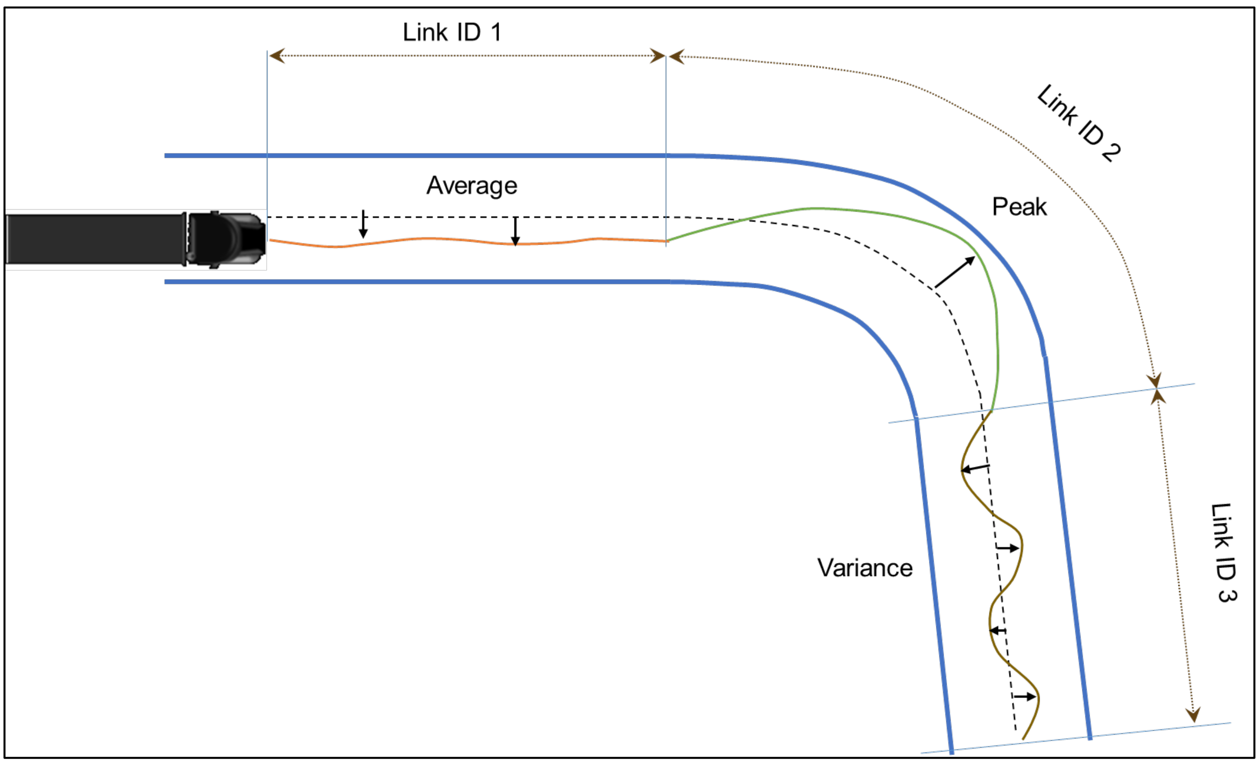


Figure 9. Illustration. Schematic defining the concept of lane stability.

Lane stability is defined by three features, or in this case statistical references, calculated from the lane offset in each link ID:

- Type 1: mean absolute value of lane deviation computed for each link ID (Note that while using absolute value, this feature does not consider whether the deviation is on the left side or right side.)

- Type 2: standard deviation of lane deviation computed for each link ID

- Type 3: maximum lane deviation computed for each link ID

For each type, the statistics were computed for specific ODDs, as defined by the interstate name, speed limit, and number of lanes. Each table shown in the following sections reports mean value, standard deviation (std), 25th quartile (Q1), 50th quartile (Q2), and 75th quartile (Q3) of a specific feature computed for the whole exposure available in the specified ODD. For example, row 1 in Table 49 shows the statistics for type 1 lane stability computed over all naturalistic data available on I-5. Here, the mean lane deviation is 8.4. inches, the standard deviation is 6.0 inches, and 75 percent of mean absolute lane deviations (Q3) are 10.8 inches or less.

4.4.6.1 Lane Stability by Highway ODDs

Tables 49, 50, and 51 show all the statistics comparing the 10 highway ODDs for lane stability types 1, 2, and 3, respectively.

Table 49. Lane stability type 1 statistics by 10 highway ODDs.

Highway ODD	Mean (inches)	Std (inches)	Q1 (inches)	Q2 (inches)	Q3 (inches)
I-5	8.4	6.0	4.4	7.0	10.8
I-10	8.3	6.0	4.3	6.8	10.6
I-20	8.5	5.9	4.6	7.2	10.9
I-35	7.7	5.5	4.2	6.4	9.7
I-40	8.3	5.8	4.4	7.0	10.7
I-70	8.5	5.9	4.7	7.1	10.6
I-75	9.1	6.4	4.8	7.6	11.7
I-80	8.8	6.2	4.9	7.4	11.2
I-95	9.1	6.2	4.9	7.7	11.8
All HW	9.1	6.2	5.0	7.7	11.5

Table 50. Lane stability type 2 statistics by 10 highway ODDs.

Highway ODD	Mean (inches)	Std (inches)	Q1 (inches)	Q2 (inches)	Q3 (inches)
I-5	4.6	4.0	2.1	3.7	5.7
I-10	4.6	4.2	2.1	3.7	5.8
I-20	4.8	4.0	2.2	4.0	6.2
I-35	4.6	3.9	2.1	3.7	5.8
I-40	4.6	3.8	2.2	3.9	6.0
I-70	5.1	4.0	2.5	4.3	6.5
I-75	5.0	4.0	2.4	4.2	6.4
I-80	5.3	4.2	2.6	4.5	6.7
I-95	4.9	4.0	2.3	4.1	6.2
All HW	5.6	4.4	2.8	4.7	7.1

Table 51. Lane stability type 3 statistics by 10 highway ODDs.

Highway ODD	Mean (inches)	Std (inches)	Q1 (inches)	Q2 (inches)	Q3 (inches)
I-5	18.0	13.3	9.7	14.8	21.7
I-10	17.9	13.2	9.7	14.8	21.5
I-20	18.4	12.9	10.1	15.5	22.4
I-35	17.0	12.4	9.2	14.1	20.4
I-40	17.5	12.2	9.7	14.9	21.5
I-70	19.2	13.4	10.7	16.2	23.3
I-75	19.4	13.3	10.6	16.2	23.9
I-80	20.3	14.0	11.3	17.0	24.5
I-95	19.1	13.1	10.6	16.2	23.4
All HW	21.2	14.6	11.6	17.7	25.7

Based on these comparisons, lane stability behavior is fairly consistent over different highway ODDs and close to the All HW ODD that represents data from all highways.

4.4.6.2 Lane Stability: Speed Limit ODDs

Tables 52, 53, and 54 compare the nine speed limits for type 1, 2, and 3 lane stability.

Table 52. Lane stability type 1 feature by ODDs with different speed limits.

Speed Limit (mph) ODD	Mean (inches)	Std (inches)	Q1 (inches)	Q2 (inches)	Q3 (inches)
40	9.3	7.2	4.7	7.4	11.7
45	10.5	8.6	5.0	8.1	13.0
50	9.7	7.0	4.9	7.9	12.5
55	9.1	6.6	4.7	7.5	11.7
60	8.3	5.9	4.5	6.9	10.5
65	9.2	6.3	5.1	7.8	11.7
70	9.0	5.8	5.2	7.8	11.4
75	9.1	5.8	5.4	7.8	11.4
80	8.4	5.5	5.1	7.2	10.3

Table 53. Lane stability type 2 statistics by ODDs with different speed limits.

Speed Limit (mph) ODD	Mean (inches)	Std (inches)	Q1 (inches)	Q2 (inches)	Q3 (inches)
40	5.7	5.3	2.5	4.3	7.0
45	5.8	5.5	2.4	4.3	7.2
50	5.6	4.6	2.6	4.4	7.0
55	5.2	4.5	2.4	4.1	6.5
60	5.0	4.3	2.4	4.1	6.3
65	5.7	4.4	2.9	4.8	7.2
70	5.8	4.3	3.1	5.1	7.3
75	6.1	4.3	3.5	5.4	7.7
80	6.2	4.1	3.6	5.5	7.8

Table 54. Lane stability type 3 statistics by ODDs with different speed limits.

Speed Limit (mph) ODD	Mean (inches)	Std (inches)	Q1 (inches)	Q2 (inches)	Q3 (inches)
40	20.8	15.5	10.6	16.4	25.1
45	22.0	16.3	10.9	17.4	26.9
50	20.6	14.1	11.2	17.0	25.4
55	19.7	14.1	10.5	16.1	23.8
60	19.1	14.0	10.2	15.5	22.8
65	21.5	14.6	11.8	18.0	26.2
70	22.2	14.8	12.6	18.8	26.7
75	23.3	15.2	13.4	19.8	27.9
80	22.8	14.9	13.1	19.1	27.3

Based on these comparisons, lane stability behavior is fairly consistent over highway segments with different speed limits.

4.4.6.3 Lane Stability by Number of Lanes

Tables 55, 56, and 57 show the number of lanes and type 1, 2, and 3 lane stability.

Table 55. Lane stability type 1 statistics by number of lanes ODDs.

Number of Lanes ODD	Mean (inches)	Std (inches)	Q1 (inches)	Q2 (inches)	Q3 (inches)
1	**16.3**	**11.4**	**8.1**	**13.5**	**21.1**
2	9.6	6.2	5.5	8.2	12.0
3	8.6	6.1	4.6	7.1	10.9
4	8.1	6.0	4.2	6.6	10.3
5	7.6	5.8	3.9	6.1	9.6
6	7.2	5.7	3.6	5.8	9.1
> 6	7.8	6.5	3.8	6.0	9.7

Table 56. Lane stability type 2 statistics by number of lanes ODDs.

Number of Lanes ODDf	Mean (inches)	Std (inches)	Q1 (inches)	Q2 (inches)	Q3 (inches)
1	10.0	7.7	4.2	8.1	14.1
2	6.1	4.5	3.3	5.3	7.7
3	5.1	4.2	2.5	4.2	6.4
4	4.6	3.9	2.2	3.7	5.7
5	4.0	3.6	1.9	3.2	5.0
6	3.8	3.6	1.7	2.9	4.6
> 6	5.0	5.8	2.0	3.4	5.4

Table 57. Lane stability type 3 statistics by number of lanes ODDs.

Number of Lanes	Mean (inches)	Std (inches)	Q1 (inches)	Q2 (inches)	Q3 (inches)
1	35.1	20.3	18.4	31.0	49.5
2	23.2	15.1	13.3	19.7	27.9
3	19.3	13.7	10.5	15.9	23.3
4	17.3	12.5	9.5	14.2	20.8
5	15.5	11.6	8.5	12.7	18.6
6	14.7	11.6	8.1	11.8	17.2
> 6	16.8	15.1	8.3	11.8	18.5

Based on these comparisons, the number of lanes plays a major role in vehicle lane stability. Highways with fewer lanes exhibit relatively poor lane stability with a higher number of lateral movements.

4.5 LIMITATION OF LEADING PERFORMANCE BASELINE

A limitation of using continuous data to develop safety performance criteria for leading performance measures is the regional nature of some collections within particular highway ODDs. The characteristics within each highway route (e.g., I-10 or I-95) vary between geographic perimeters and State boundaries. The heat maps of the trips traveled by the CMVs are presented in Appendix C.

However, the application here of a large and continuous highway data collection for human operated CMVs provides a starting point for ADS manufacturers and developers to build and refine CMV performance criteria for range of recommended and not-recommended maneuvers for ADS-equipped CMVs. Further examination of road features among ODD variables may expand the range of roadways on which ADS-equipped CMVs could operate. The findings here start this examination by providing a baseline of leading human operated CMV performance under various speed limits and numbers of lanes.

5. CONCLUSIONS

Lagging performance measures, such as crashes, can serve as an important measure of safety for human operated and ADS-equipped CMVs. This study delivered a baseline of observed crash rates for Class 8 trucks on specific highway ODDs across the United States. Near-crashes may also be adopted as lagging indicators by developers of ADS-equipped CMVs to track ADS performance. This study also delivered a baseline of observed near-crashes for Class 8 trucks on the same highway ODDs across the United States.

Leading performance measures, such as longitudinal (e.g., following distance) and lateral (e.g., lane deviation) maneuvers, can also provide objective and currently available measures of real-time performance. Developers, evaluators, and regulators may choose to apply such measures to compare ADS and human performance, and assess changes in human driving performance as a result of increased use of ADS and ADAS technologies.

5.1 LAGGING BASELINE OF CONVENTIONAL CMV PERFORMANCE

Lagging baseline categories and criteria cover a wide range of driver behaviors in the context of crashes and near crashes. The complete list is represented in Section 3: Lagging Baseline Results. In general, results reflected correlations between crash and near-crash rates and naturalistic data representing:

- Operational design domains
- Crash severity
- Crash type
- Vehicle involvement rates
- Environmental conditions
- Observed inattention behaviors
- Observed negative (non-inattention) behaviors

The results facilitate specific comparisons between ADS-equipped CMV performance and current human driver performance. They also allow analysis of crashes and near crashes by likely cause, facilitating estimates of how many and which crashes ADS technologies are likely to prevent or mitigate.

- As described in Table 3, the crash rate per 100 million VMT on all U.S. highways in this study was 109.9. Among the nine highways specified as individual ODDs, I-95 had the highest crash rate at 136.4. These crashes were observed, and the sample is confined to highways. The closest comparison to other public records of crash rates is to the rate of reported combination truck crashes that include fatality, injury, and property damage only on all roadways, which includes interstate, arterial, and other roads across both urban and rural environments. These rates are reported by FMCSA in *Large Truck and Bus Crash Facts 2017*. According this resource, in 2017 there were 137.8 crashes per 100 million

VMT involving combination trucks. The roadway types included in this rate are broader than the ODD defined in Table 3, and the rates on U.S. highways found in this study also include low level crashes that often go unreported.

- As described in Table 4, the rate per 100 million VMT of high-severity crashes on all U.S. highways considered was 2.4, while the highest rate of high-severity crashes among the study's nine highway ODDs was 5.0 on I-80. The rate per 100 million VMT of police-reportable crashes on all U.S. highways was 81.3, and the highest rate was 109.0 on I-95. The rate per 100 million VMT of minor crashes on all U.S. highways was 23.0, and the highest rate was 29.6 minor crashes on I-35.
- The two most frequent crash types on all U.S. highways were (1) conflict with an object in the roadway and (2) conflict with a vehicle in an adjacent lane, both having rates of 28.4 crashes per 100 million VMT, as shown in Table 5.
- In a majority of crashes involving Class 8 trucks with interior cameras, drivers were not observed to be involved in secondary tasks (see Table 6). Similarly, in a majority of crashes drivers were not observed to be engaged in negative driving behaviors (see Table 7).
- The most common unexpected event identified during crashes involved debris hitting the CMV or an animal/pedestrian running in front of the vehicle on the highway (see Table 8).
- As described in Section 3.3.3.6, the majority of crashes occurred during dry, clear, and daylight conditions. These conditions fit into the ODD profile of near-term deployment of ADS-equipped CMVs.
- CMV drivers were involved in 74.8 crashes per 100 million VMT in which they were judged *not* to have been at fault based on experimental video review (see Table 25). Among crashes where drivers were judged to be at least partially at fault, the highest rate (12.6 crashes per 100 million VMT) occurred when negative behaviors were present but the drivers were attentive and no unexpected event occurred. These negative behaviors commonly included lane drifting and following too closely (see Table 7). CMV drivers involved in at-fault crashes had a negative behavior or inattention component present in 29.4 crashes per 100 million VMT (84 percent of all at-fault). ADS-equipped CMVs may be effective at mitigating or avoiding such crashes in the future.
- The research term studied near crash rates for each ODD. The rate of near-crashes (781.6 per 100 million VMT) was much higher for I-95 than the rate for all U.S. highways (487.2 per 100 million VMT) and higher than rates for the other eight specific highway ODDs. I-40 had the lowest rate, at 288.7 per 100 million VMT.

5.2 LEADING BASELINE OF CONVENTIONAL CMV PERFORMANCE

A range of conventional vehicle maneuvers was defined in this study to illustrate examples of near-term, objective, and widely accepted leading performance measures. These maneuvers exhibited longitudinal properties, such as speed behavior, longitudinal deceleration (i.e., braking), and following distance, as well as lateral properties, such as lateral acceleration, lane deviation, and lane stability. Many of these maneuver attributes are incorporated into current production ADAS technologies. Developers in the future will need to resolve the tactical decisions that the ADS will perform. But those tactical decisions will be in the form of algorithms that will probably be proprietary. In the future, criteria for leading performance characteristics could be assigned based on the findings from this non-proprietary study to verify safe and unsafe maneuvers performed by ADS-equipped CMVs.

5.2.1 Traveling Above or Below the Posted Speed Limit

The speeding behavior documented in Section 4.4.1.2 is informed by highway limits, vehicle specifications, and traffic on highways. Maximum speeds are often limited by vehicle specifications, such as electronic speed governors which cap speeds at 65 mph under manual control and cap them slightly higher while cruise control is active (e.g., 68 mph). Therefore, conventional CMVs operate at vehicle speeds below the limit on highways with higher speed limits (e.g., 75 mph) due to fleet policy and operate at vehicle speeds above the limit on highways with lower speed limits (e.g., 45 mph), though less frequently, based on traffic flow or other factors. Some highways have posted speed limits for CMVs that vary from those assigned to the datasets in this analysis. The varying speed limits were not considered in this analysis.

5.2.2 Longitudinal Deceleration

As described in Section 4.4.3.2, conventional CMVs operating on roadways with speed limits below 65 mph have much higher deceleration rates per 1,000 miles. For example, type 1 deceleration rates between 0.1 and 0.2 g on 60-mph speed limit roads occur at a frequency of 62.6 per 1,000 miles compared to a frequency of 32.7 per 1,000 miles at 65 mph. Similarly, type 2 deceleration rates between 0.2 and 0.35 g on 60-mph speed limit roads occur at a frequency of 11.0 per 1,000 miles compared to a frequency of 4.2 per 1,000 miles at 65 mph. Those rates increase more on sections of highways with lower speed limits. ADS-equipped CMV developers that intend for those vehicles to move among other truck and light vehicle traffic in lower speed limit zones should anticipate more frequent decelerations or possibly bring the human operator into an engaged monitoring state prior to entering this highway ODD.

5.2.3 Following Distance

As described in Section 4.4.4.2, following distance performance changes by speed limit. These results demonstrate that the most frequent following distance cases, defined in terms of a minimum following time of 3 minutes, occur between 1 and 2 seconds (type 2) and 2 and 3 seconds (type 3). For those two types, the frequency of following distance cases is higher at the lower speed limit ranges. These speed limits are likely required due to high-traffic highway zones and within highway interchange zones. One resulting possible design consideration for ADS-equipped CMVs is allowance for close following distances to prevent an ADS-equipped CMV from responding so cautiously that it cannot merge or proceed on its tactical path.

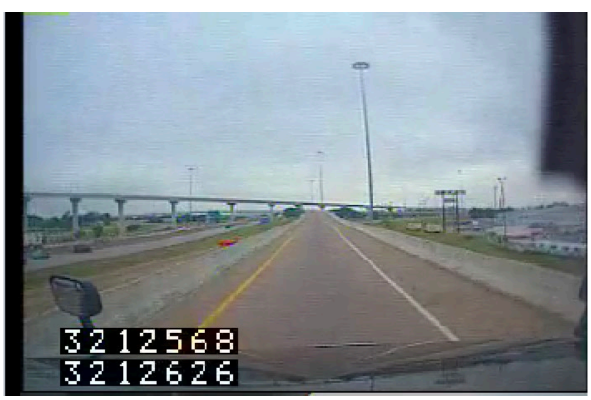
5.2.4 Lane Deviation in Single Lane

As shown in Section 4.2.5.3., lane deviation characteristics are different for single lane highways than for highways with more than one lane. The significance of this point can be demonstrated by the number of miles drivers traveled while deviating outside of their lane, meaning the number of miles in type 2 or greater lane deviation. On single lane highways, drivers drove 220 aggregated miles outside the lane for every 1000 miles driven; whereas on sections of highway with more than one lane, drivers drove a maximum of 40 aggregated miles outside the lane for every 1000 miles driven.

To understand this behavior, the research team examined the naturalistic videos for the single lane ODD. Most type 2, 3, and 4 deviations occurred on connectors between two highway segments. There are three main explanations for the high lane deviation. First, the vehicles passed through a roadway transition where the drivers had to merge lanes or take exits. This tactical decision-making may divert the driver's attention from lateral control. Second, as vehicles travel through a single lane, drivers may feel that, as there are no vehicles in the adjacent lane, they have more flexibility in lane-keeping behaviors. Third, ramps typically have higher curvature, and due to vehicle momentum, the vehicle tends to deviate more than on multilane highway driving. Figure 10 provides four examples of single-lane roadways considered in this interstate ODD.

(a)

(b)



(c)

(d)

Figure 10. Video stills. Single-lane road examples.

5.2.5 Lane Stability

Lane stability is the inverse of lane deviation. Rather than the rate at which conventional drivers move left or right of center, lane stability is a measure of on-center performance. As described in Section 4.4.6.3, the same pattern seen in lane deviation appears in the single-lane case of lane stability. This may be used as a reference for the maximum allowable movement within the lane as drivers focus on the tactical tasks of dealing with traffic and transferring between highways and around ramps, which can result in wandering.

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APPENDIX A. DATASET REVIEW QUESTIONS

Fleets, vehicle types, and operating environments

a. What types of trucks are included?

b. Is there information available on whether the involved trucks were equipped with driver support- or lower-level automated driving functions?

c. How many and what types of fleets are included?

d. What types of transportation operations were the trucks performing?

e. Sites and routes

Data collected

a. Number of consenting drivers, mileage, and time duration

b. Signals included and DAS used

c. Specific experimental conditions

SCEs and unsafe behaviors

a. What SCEs/behaviors have already been identified?

b. What is the frequency of identified SCEs/behaviors?

c. What types of new SCEs/behaviors can be extracted from the data?

Exposure information

a. What exposure variables (e.g., mileage, hours of driving) are available?

b. How were the exposure variables calculated?

Possibilities for safety metric calculation

a. For what types of events and behaviors can true rates be obtained?

b. For behaviors extended in time (e.g., speeding, seat belt use), is it possible to calculate the true proportion of exposure (e.g., % VMT speeding)?

c. If true rates or proportions are not available or possible to calculate, can they be estimated?

Possibilities for Operational Design Domain (ODD) identification

a. Do the data contain GPS and map data and has map matching been conducted?

b. What types of other information are available for mining the data with respect to different ODD conditions?

c. Is there information available on the geographical distribution of the data?

Information on individual drivers and fleets

a. Are the data annotated with driver ID and fleet codes?

b. Do the available driver IDs distinguish between different individuals driving the same vehicle?

c. Is there information available on driver demographics, driving history, personality screening etc.?

d. Is there information available on whether drivers were involved in safety programs, etc.?

e. Are there restrictions (e.g., related to informed consent, customer agreements, etc.) on the extent to which driver and fleet identity data can be used for the analysis (e.g., to obtain CSA scores for fleets)?

Evaluation of the suitability for establishing a human safety performance baseline for ADS-equipped CMVs

Evaluate the usefulness of the dataset for the purpose of establishing a human safety performance baseline for ADS-equipped CMV.

APPENDIX B. CLASS 8 TRACTOR TRAILER ODD FRAMEWORK

Operational Design Domain, Reference Set Categories, Variables, and Gradations for Class 8 Commercial Tractor-Trailer ADS

Categories[2]	Elements[2]	Variable	Status	Gradation (near-term)		Gradation (mid-term)		Gradation (far-term)		L3 Highway Gradation Examples[2]
Physical Infrastructure	Roadway Types	Roadway type	Static	private	primary	secondary		local		Interstates, freeways, divided highways, arterials, urban, bridges, multi-lane, single-lane, one-way, tunnels
		Geographic Area	Static	desert/forest/field	rural	mountain		urban	city	
		Access	Static	limited, interchange ramp		unlimited, traffic light controlled		unlimited, stop sign controlled	round-about	
		Lanes (same direction)	Static	3+, divided	2, divided	1, divided		1, undivided		
	Roadway Surfaces	Road Surface	Static	paved/painted	bridges	tar & chip (painted)		gravel	unimproved	Asphalt, concrete, mixed
	Roadway Edges and Markings	Lane Markings	Quasi-Static	high contrast		low contrast	concrete barriers[2]	cones[2]	inconsistent / none	Lane markers, temporary lane markers, concrete barriers, curbs, cones
	Roadway Geometry	Shoulder Width, Outside [1]***	Static	> 10 feet (12 or more feet*)	10 feet	8 feet		1-7 feet	< 1 foot	
		Road Grade (slope)	Static	< 1%	1-3%	3-6%		6-10%	>10%	
		Road Radius of Curvature (update specific)	Static	negligible	large	medium		small (i.e., rollover risk speed zone)		
		Visibility Around Curve	Quasi-Static	clear		obstructed		blocked		
Operational Constraints	Minimum Speed Limit	Speed Limit Min (mph)	Static	max -15 mph	max -15 mph	max - 15 mph		na		72 kph (45 mph) (notionally)
	Maximum Speed Limit	Speed Range (mph)	Static	> 65	64-55	54-45	< 25	44-35	34-25	112 kph (70 mph) (notionally)
	Traffic Density	Traffic Density	Dynamic	none	light	moderate	stop-n-go	heavy		Minimal, nominal
Environmental Conditions	Weather	Environmental, Weather	Dynamic	dry[2]		light rain	light snow	heavy rain	heavy snow / ice	Clear, calm
	Weather-induced Roadway Conditions			clear / calm[2]		windy		heavy wind		Dry
	Illumination	Environmental, Light	Dynamic	day, between 90°-20°	dawn / dusk / night	day, a < 20°	day, road shaded			Day, dawn/dusk
		Lighting, Night [1]	Static	> 5 lux	2-5 lux**	none				
Connectivity	Digital Infrastructure	V2X BSM Connectivity[2]	Dynamic	Class 8 platooning		any vehicle	roadway	pedestrian / cyclist		Optional to determine if inside or outside of zone
Zones	Region / States	Regulatory Boundary[2]	Static	federal		state		city / town / village / borough		Adhere to state/local laws
	School / Construction	Construction[2]	Quasi-Static	none		constr. inactive		constr. active	school open / closed	Construction zones
	Interference	Live GPS[2]	Quasi-Static	GPS consistent		GPS inconsistent		GPS unavailable		Urban canyons

1: AASHTO (2011). Policy on geometric design of highways and streets. (6th Ed). American Association of State Highway and Transportation Officials, Washington, DC.
* Twelve feet required when truck traffic exceeds 250 vehicles/hour
** Street lighting can increase conspicuity of other vehicles at locations of high rate of change between vehicles in relative speed and across lanes.
*** Shoulder width provides immediate solution for L4 ADS-DV to revert to low-risk condition by pulling off the highway
2: Thorn, Kimmel, and Chaka (2018) NHTSA Framework for ADS Testable Cases and Scenarios

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Figure B-1. Class 8 tractor trailer ODD framework.

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APPENDIX C. HEAT MAPS OF U.S. CONTINUOUS COLLECTIONS

Figures C-1, C-2, C-3, C-4, and C-5 show the distribution of travel mileage for the OBMS FOT 1, OBMS FOT 2, FAST DASH 1, FAST DASH 2, and FAST DASH 4 databases. The color represents the frequency of travel in each road segment. For example, black indicates roadway segments with more than 300 trips recorded in the database. Combinations of all trips from all the datasets span the United States, covering major highways. The major concentration of the collected data is in the eastern and southern part of the country. Table C-1 shows a summary of all the trips indicating high volume data for six major highways and in the different states.

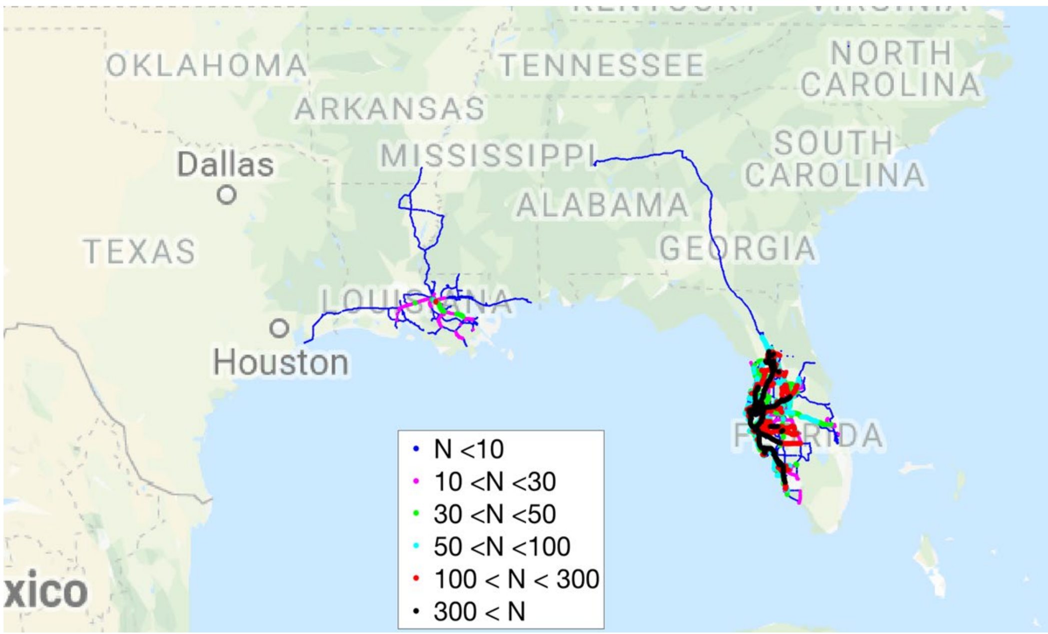

Figure C-1. Map. Travel mileage covered during OBMS FOT 1 database collection. "N" represents the frequency of trips on a specific roadway segment.

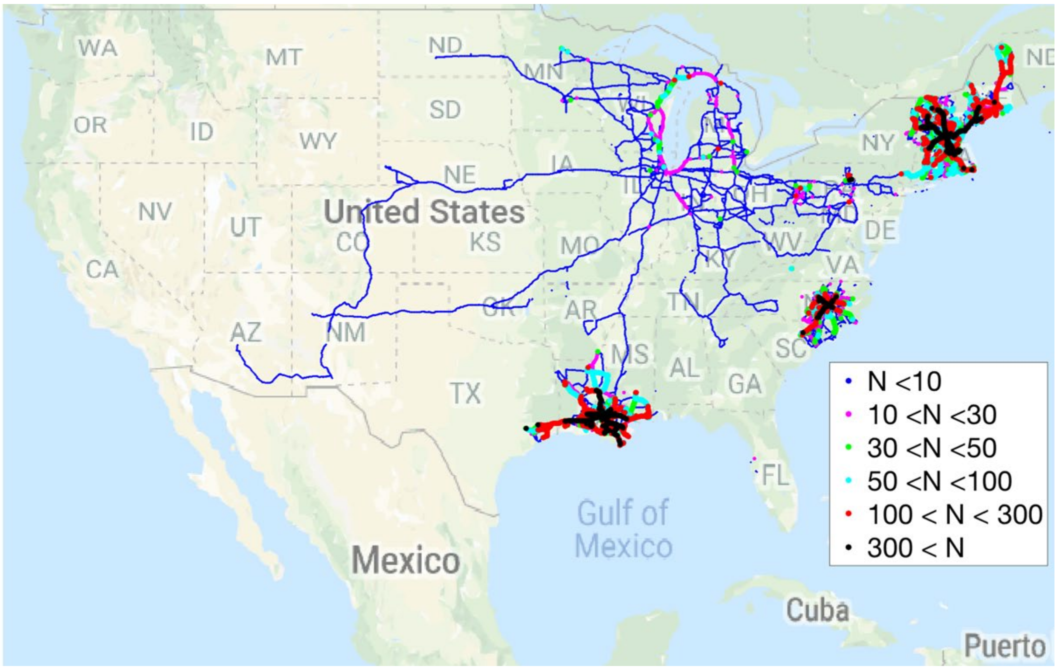

Figure C-2. Map. Travel mileage covered during OBMS FOT 2 database collection. "N" represents the frequency of trips on a specific roadway segment.

FAST DASH EVALUATION 1

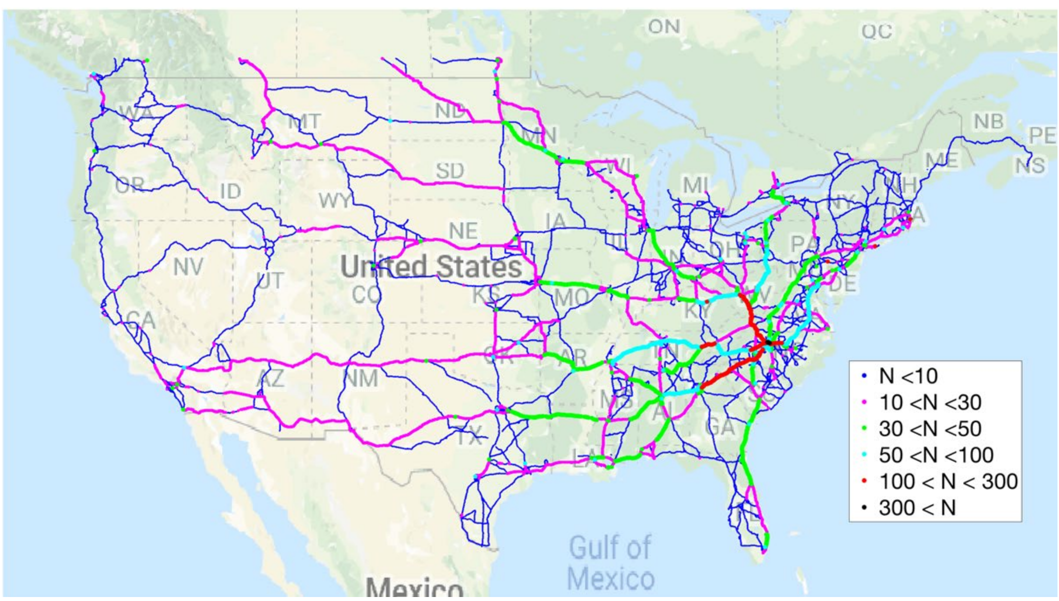

Figure C-3. Map. Travel mileage covered during FAST DASH 1 database collection. "N" represents the frequency of trips on a specific roadway segment.

FAST DASH EVALUATION 2

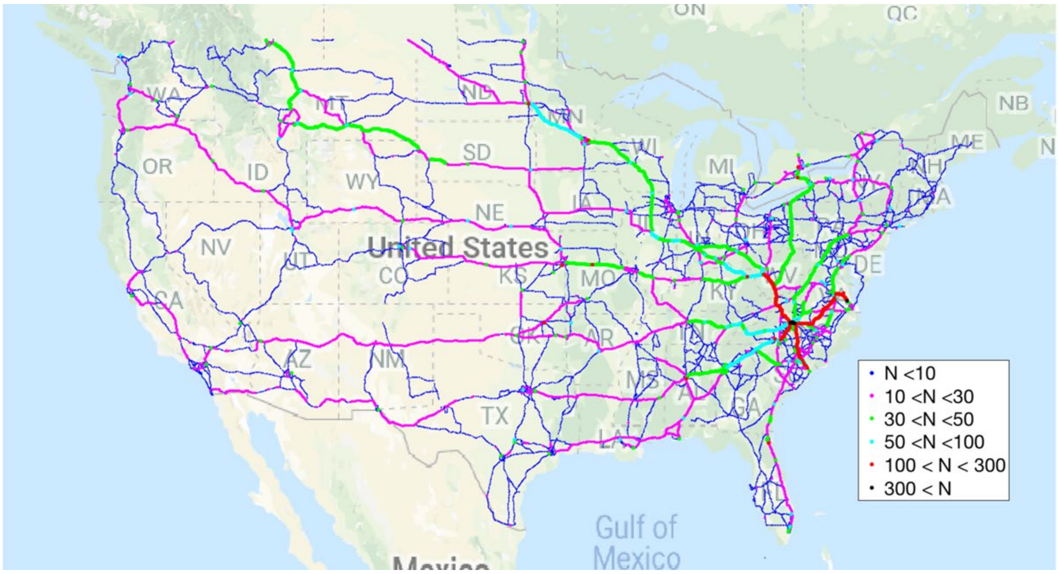

Figure C-4. Map. Travel mileage covered during FAST DASH 2 database collection. "N" represents the frequency of trips on a specific roadway segment.

FAST DASH EVALUATION 4

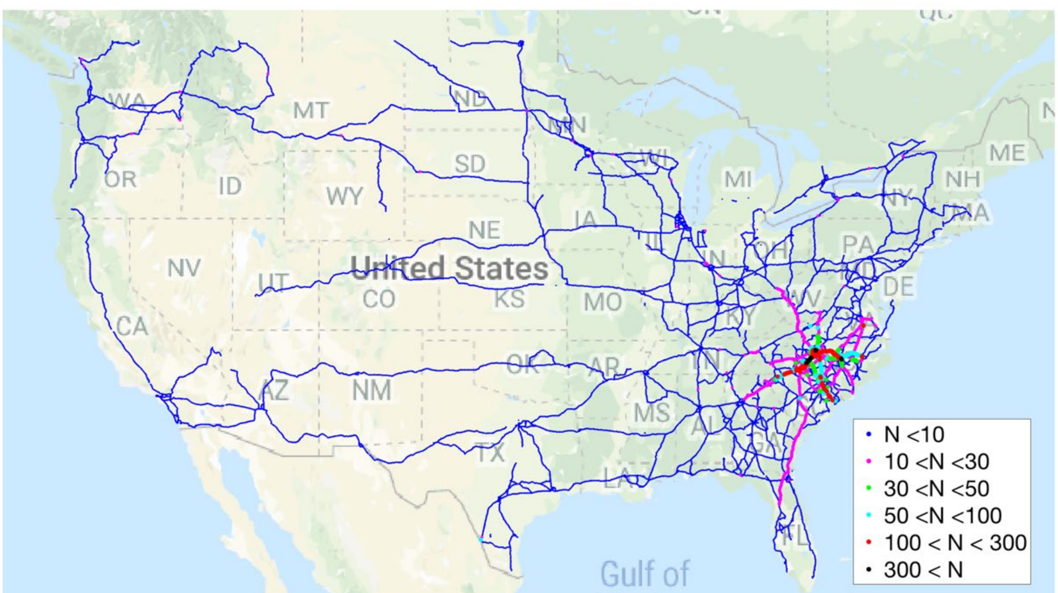

Figure C-5. Map. Travel mileage covered during FAST DASH 4 database collection. "N" represents the frequency of trips on a specific roadway segment.

Table C-1. Summary of continuous trip data with high volume (more than 100 trips) by State and interstate highway.

Route	States
I-20	GA, AL, MS, LA, TX
I-40	NC, TN, AR, OK, NM, AZ, CA
I-70	MO, NC
I-75	FL
I-95	GA, FL, NC, SC

APPENDIX D. NATURALISTIC EVENT DATA REDUCTION

Data Collected

The collection system typically provides two camera views, one audio channel, GPS data, and various data elements from the vehicle network (e.g., J1939), including data from any active safety systems installed on the truck (e.g., collision avoidance system, lane departure warning, rollover protection, and stability control). An example of the two-camera view is given in Figure D-1. However, the number of cameras used may vary depending on customer preferences. Different possible camera configurations are illustrated in Figure D-2.

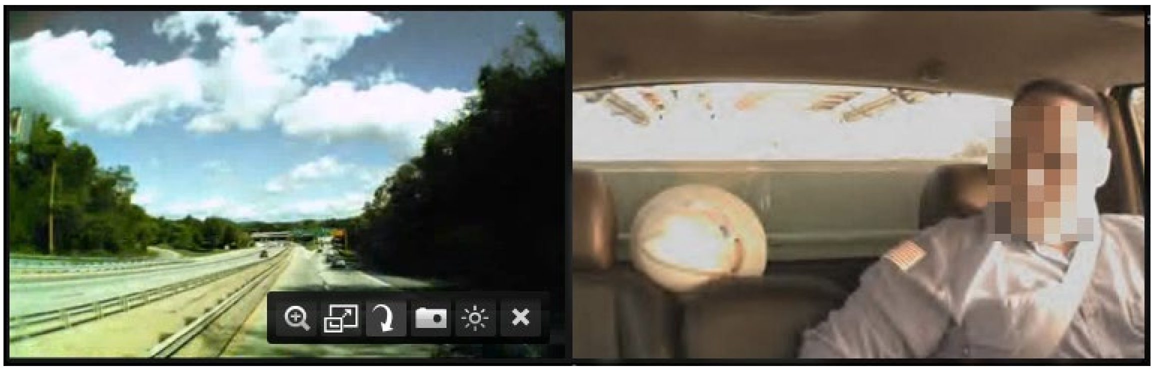

Figure D-1. Screenshot. Two-camera view recorded by the onboard monitoring unit.

Figure D-2. Diagram. Examples of possible camera configurations with the onboard monitoring unit.

Events are triggered by kinematic or other sensory signals. Event data contain the video streams (at 4 Hz), audio, sensor data from the collection unit, engine control unit data from the vehicle's network (in trucks, typically obtained via the J1939 CAN bus), and general metadata. The sensor data recorded by the unit include GPS; *x*, *y*, and *z* acceleration; and GPS based speed.

The external signals recorded from the J1939 CAN bus are usually the same as those recorded in the datasets (e.g., vehicle speed, pedals, and signals from active safety systems). External data may also include signals from other onboard sensors not connected to the vehicle network. The exact set of triggers and available external signals may differ from vehicle to vehicle and may include ADAS triggers. Moreover, the threshold values used for triggers are adjusted for each customer to obtain a target event rate agreed upon with the client. Information on trigger type was collected as part of the data associated with each event. Event and trip slice data are typically offloaded over the air automatically, and the events are analyzed manually for unsafe behaviors.

Safety-critical Events (SCEs) and Unsafe Behaviors

Each triggered event was analyzed by trained data reductionists based on a data dictionary developed in-house at the vendor. The reduction variables are referred to as *observations* and include a classification of crash and near-crash outcomes, various unsafe driver behaviors and driver errors (e.g., mobile phone texting, unsafe following, failure to yield, etc.), and observations related to the vendor equipment (tampering, suboptimal camera position, etc.).

For the present data query (Class 8 trucks only over the 2-year period), 60 percent of the 14.16 million events did not contain any observations at all and their video data were thus discarded after 30 days.

While some clients of the vendor only chose to use the forward camera, in other cases drivers may have tampered with the unit, or the camera system may not have functioned optimally. Taking these factors into account, during the 2-year period of data collection, driver camera footage was available for 48 percent of the recorded events. About 13,000 of the collected events involved crashes, and there were about 28,000 near-crashes. These statistics represent all recorded activity and not only highway driving, the ODD of interest to this study.

Event Data Reduction

The event data covered 3.44 billion miles and approximately 56 million hours on primary roads. Trips were excluded if the collection unit was malfunctioning or unable to upload data due to technical or tampering issues. The three reduced event types are outlined and described in Table D-1 along with the sampling methodology performed by the vendor.

Table D-1. Event types and descriptions from event data.

Event Type	Sampling Method	Description
Collision (crash)	Complete Population	Event involving any contact that the subject vehicle has with an object, vehicle, or person, or an event involving non-premeditated departures of the roadway.
Near-collision (near-crash)	Complete Population	Event involving any circumstance where the subject vehicle came dangerously close to being in a collision.
Behavioral Observation	Randomly Sampled	A kinematic-triggered, ADAS-triggered, or similar triggered event in which no collision nor near-collision occurred.

Crash Data Reduction

The crashes were verified through video review by the vendor's reduction laboratory prior to this research. In June 2018, the research team sent a data reduction coordinator to the vendor's headquarters to provide training in the reduction processes used for the Second Strategic Highway Research Program (SHRP 2). This training consisted of using the video data and software interface to reduce SHRP 2 variables on 25 randomly sampled crash events. The vendor then trained their data reduction team to apply the SHRP 2 data dictionary classification to the crashes.[24] The events were classified into the following crash categories:

- Single-vehicle conflict
- Conflict with a lead vehicle
- Conflict with obstacle/object in roadway
- Conflict with animal
- Conflict with vehicle in adjacent lane
- Conflict with merging or weaving vehicle
- Conflict with a following vehicle
- Conflict with parked vehicle
- Conflict with out-of-control vehicle in roadway
- Conflict with pedestrian
- Other

The final step of the SHRP 2 protocol called for the reductionists to develop an annotation of the event context. In order to increase reduction efficiency, the vendor's reduction lab asked for a simplified method of annotation. The primary purpose of the annotation for this project was to identify unexpected events. Therefore, the research team classified the most prominent unexpected events into 10 categories with an additional "other" option for comment:

- Animal or pedestrian runs in front of subject vehicle
- Debris hits subject vehicle
- Motorcycle splitting lanes around subject vehicle
- Second vehicle pulls out in front of the subject vehicle unexpectedly
- Second vehicle encroaches into subject's lane
- Second vehicle brakes suddenly in front of subject vehicle
- Another vehicle cuts in front of subject vehicle
- Changes in traffic happen while the subject is not paying attention
- Other vehicle crash occurring around subject vehicle
- None
- Other, please specify in additional commentary

During reduction, the reductionists defaulted to “other” in many cases and never applied “none.” Therefore, to fulfill the objectives of this study, the research team further specified the unexpected events or moved them to the category of “none” if no unexpected event occurred. Additionally, the research team confirmed or modified the assignment of driver fault across all crashes. There were 3,781 crash events identified for this research.

Near-Crash Data Classification

Triggered events identifying potential near-crashes were also verified through video review by the reduction laboratory prior to this research. The events were classified into the following near-crash categories:

- Near crash with animal
- Near crash with fixed object
- Near crash with other movable object
- Near crash with parked vehicle
- Near crash with pedalcycle
- Near crash with pedestrian
- Near crash with train
- Near crash with vehicle in transport
- Near crash with work zone equipment

There were 16,767 near-crash events identified for this research.

Non-Crash Data Classification

In addition, a random sampling of all non-crash related driving behaviors was created across all Class 8 truck highway events, in which a non-crash event is recorded based on at least one triggered event occurring in the truck. The triggered events were independently verified through video review by the vendor’s reduction laboratory prior to this research. The events were classified into the following higher-order behavior categories:

- Unprofessional driving
- Vehicle control
- Stopping
- Speeding
- Situational awareness
- Distraction
- Fatigue
- Seatbelts

- Unprofessional conduct

These nine categories were further broken down into 47 specific behavioral observations, which are detailed in the results sections (Sections 3 and 4). There were 79,136 driving behavior events identified for this research.

Secondary Reduction and Quality Assurance

After the vendor delivered the crash data, the research team performed a data quality check on all crashes. This additional step was beneficial to confirm the classification of both fault assignment and the unexpected events. The team conducted a quality assurance (QA) review on all crashes with an unspecified unexpected event (70 percent interrater agreement), and on all crashes with the driver-facing camera available for fault assignment (85 percent interrater agreement). Disagreements were resolved through VTTI expert review, and events were updated based on QA review results.

Fleet and Driver Description

Event and trip data included information on drivers and fleets. The data were annotated with (de-identified) driver IDs and fleet codes. The available driver IDs distinguish between different individuals driving the same vehicle, based on fleet schedule and/or dispatch (keypad) data. There is no information available on driver demographics, driving history, personality screening, or whether drivers were involved in carrier safety programs.

Restrictions exist on the extent to which driver and fleet data could be used for the present analysis: the identity of clients could not be disclosed and the driver data had to be de-identified.

Data Organization

The vendor delivered 4,097 crash events, but some crashes were secondary crashes that occurred after a primary incident. In producing the lagging baseline, only the details of the primary crash and any applicable complementary information regarding a secondary crash were kept, with the intent to capture all relevant variables within one crash. As an example, a crash in which the subject vehicle was sideswiped by a second vehicle but then ran off the road was compiled into one crash event.

Secondary crash events were removed from the total based on three parameters. First, the primary trigger for these events was an "extended recording," which captures a 30-second video before or after an event triggered by some other means. The extended recording is typically used by fleets to gather contextual information. These extended recordings were flagged during this process if they occurred on a vehicle with other crashes. Second, the crash event timing was used to determine the proximity of events. Third, crash and environmental characteristics were used to verify the removal of the crash events.

Further data cleaning was required on behavioral observation events. The vendor delivered 79,136 events randomly pulled from a total of 1,165,278 events during the 2-year collection period. These behavioral observation events included some observations made during near-crashes. The events with a near-crash present, a total of 396 events, were removed from analyses involving behavioral observations. This resulted in 78,745 sampled events. Because multiple near-crashes could occur and be recorded within the same triggered event, there are an estimated 1,159,521 total behavioral observational events.

Data Assumptions

The nature of the collection and sampling methodologies required some generalizations when creating benchmarks for crash and near-crash events involving in-cab activities. Additionally, the set of observational behavior events was limited to events that contained at least one unsafe driving behavior. The research team excluded events with no unsafe driving behaviors.

First, driver related behaviors were recorded based on the driver-facing video and/or audio during the crashes. These behaviors were most inattention behaviors, such as distraction or fatigue. In contrast, other negative driving related behaviors, such as speeding and lane drifting, can be identified with a forward roadway camera.

Of the 3,781 identified crashes, 2,120 (56.1 percent) had driver-facing video. Reduction involving driver inattention could be performed only on crashes with driver-facing video. As such crash rates involving driver inattention and similar behaviors must be adjusted accordingly to produce accurate rates by exposure. This is necessary because exposure in VMT and hours driven was calculated on the full dataset of vehicles, and exposure breakdown by vehicle is not available.

This 56 percent adjustment statistic was used to estimate rates of crashes when driver-facing camera was not available. This is done under the assumptions that (1) driver behaviors are similar between drivers with and without driver-facing cameras and (2) drivers in fleets that choose to install driver-facing cameras behave similarly to drivers in fleets that choose to install only forward-facing cameras. The adjusted crash rates were then calculated using the inverse of the adjustment statistic, as seen in Equation D-1:

Equation D-1. Data adjustment for crash rate based on driver-facing video availability.

$$Adjusted\ Crash\ Rate_i \quad = \frac{Crashes\ with\ Driver\ Behavior\ i\ \times inv(0.561)}{Total\ VMT\ under\ the\ Highway\ ODD}$$

Second, the proportion of driver-facing cameras cannot be estimated for near-crashes. However, given that near-crashes are typically correlated with crash events, the near-crash rates involving driver inattention behaviors were also calculated using the inverse of the 56 percent adjustment statistic, as seen in Equation D-2: [25]

Equation D-2: Data adjustment for near-crash rate based on driver-facing video availability.

$$Adjusted\ Near-crash\ Rate_i \quad = \frac{Near\text{–}\ crashes\ with\ Driver\ Behavior\ i\ \times inv(0.561)}{Total\ VMT\ under\ the\ Highway\ ODD}$$

Third, although an estimated 1,159,521 total observational behavior events were recorded, any data collected by following a trigger but without behaviors were not available for analysis. As such, it is impossible to get an accurate representation of the true behavioral event rates, as blank events are nonexistent. Therefore, only generalizations comparing behavioral observations under the same ODDs are possible.

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APPENDIX E. CANADIAN CONTINUOUS NATURALISTIC TRUCK DATASET LEADING PERFORMANCE

EXPOSURE FOR LEADING FEATURES

The exposure in total miles for the Canada data was calculated for the All HW ODD, six speed limit ODDs, and four lane number ODDs. The exposure in total miles was used to calculate miles or case rates per feature type in each of the ODDs for the leading features of speed behavior, lateral acceleration, and longitudinal deceleration, using the same methods described for U.S. data in the report.

It should be noted that due to difference in operating conditions and driving norms, the following changes were made in comparison to the U.S. data.

1. Highway definition: In the U.S. data, a highway is defined where the road has controlled access and is restricted by a certain functional class (type of vehicle, minimum speed, etc.). For the Canadian data, these ODDs were not filtered by controlled access. This is mainly due to the type of roads where the dataset was collected.
2. The minimum speed limit considered for the Canada study is 37 mph compared to the 40 mph speed limit used with the U.S. data.

Table E-1. Distribution of vehicle miles per 1,000 miles exposure in highway Canada ODD.

Highway Canada ODD	Exposure in Total Miles, Canada
ALL HW	654,815.8

Table E-2. Distribution of vehicle miles per 1,000 miles exposure by six speed limit highway Canada ODDs.

Speed Limit ODD (mph)	Exposure in Total Miles, Canada
37	4,832.1
43	9,889.3
50	11,607.1
56	77,889.7
62	178,412.8
68	372,184.6

Table E-3. Distribution of vehicle miles per 1,000 miles exposure by number of lanes highway Canada ODDs.

Number of lanes ODD	Exposure in Total Miles, Canada
1	170,584.6
2	463,156.0
3	17,526.0
4	2,889.0

SPEED BEHAVIOR

The following section presents speed behavior in the Canada dataset. Speed behavior, as change (Δ) in average speed compared to posted speed limit, is defined by eight attributes calculated from the vehicle network (J1939) speed signal in each link ID.

- All: speed limit ≥ 37 mph
- Type 1: −15 mph Δ < speed behavior ≤ −10 mph Δ
- Type 2: −10 mph Δ < speed behavior ≤ −5 mph Δ
- Type 3: −5 mph Δ < speed behavior ≤ 0 mph Δ
- Type 4: 0 mph Δ < speed behavior ≤ 5 mph Δ
- Type 5: 5 mph Δ < speed behavior ≤ 10 mph Δ
- Type 6: 10 mph Δ < speed behavior ≤ 15 mph Δ
- Type 7: 15 mph Δ < speed behavior ≤ 20 mph Δ
- Type 8: 20 mph Δ < speed behavior

The data are presented for all highways (one single highway ODD), six different speed limit ODDs, and four number of lane ODDs.

Speed Behavior by Highway ODD

Table E-4. Distribution of vehicle miles per 1,000 miles exposure on highway Canada ODD for each type of speed behavior.

Highway Canada ODD	Type 1 (15 to 10 mph below limit)	Type 2 (10 to 5 mph below limit)	Type 3 (5 to 0 mph below limit)	Type 4 (0 to 5 mph above limit)	Type 5 (5 to 10 mph above limit)	Type 6 (10 to 15 mph above limit)	Type 7 (15 to 20 mph above limit)	Type 8 (Over 20 mph above limit)
ALL HW	27.1	131.6	512.7	226.2	51.8	4.9	0.7	0.4

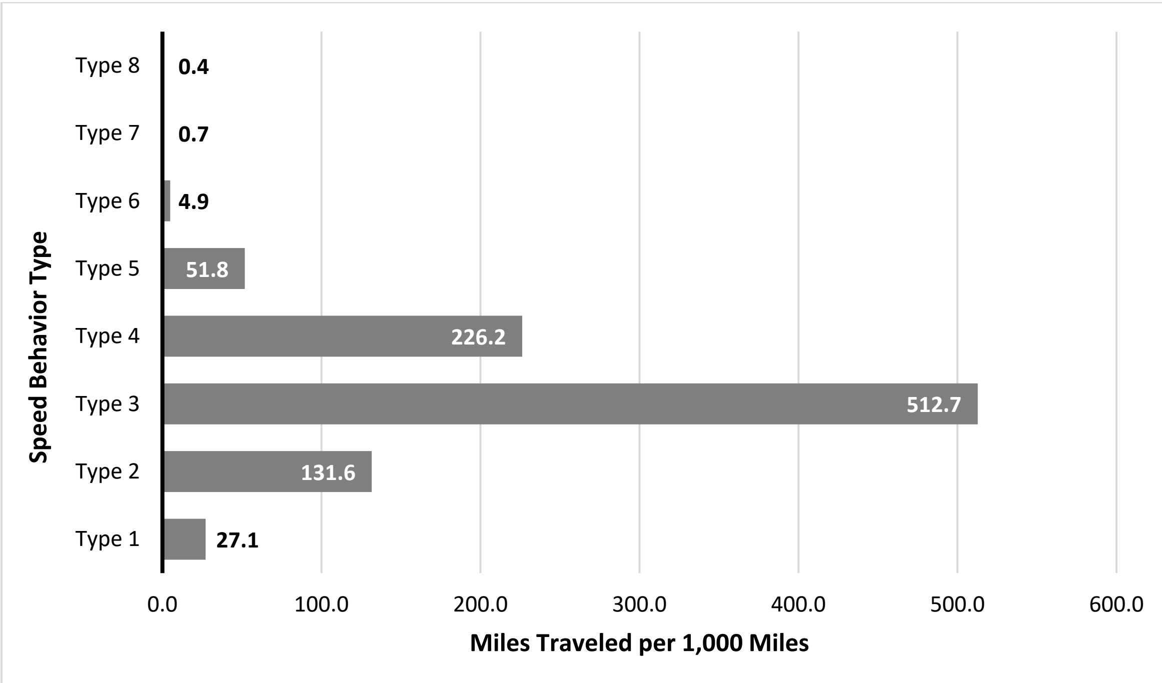

Figure E-1. Chart. Highway miles traveled (per 1,000 miles traveled) on highway Canada ODD for all 8 speed behavior types.

Speed Behavior by Speed Limit ODDs

Table E-5. Distribution of vehicle miles per 1,000 miles exposure in each speed limit Canada ODD for each type of speed behavior.

Speed Limit (mph) Canada ODD	Type 1 (15 to 10 mph below limit)	Type 2 (10 to 5 mph below limit)	Type 3 (5 to 0 mph below limit)	Type 4 (0 to 5 mph above limit)	Type 5 (5 to 10 mph above limit)	Type 6 (10 to 15 mph above limit)	Type 7 (15 to 20 mph above limit)	Type 8 (Over 20 mph above limit)
37	63.6	121.0	213.3	274.9	79.0	44.1	13.0	**21.9**
43	66.9	95.0	204.8	282.1	152.6	**78.6**	**17.3**	13.2
50	**81.2**	122.5	257.6	248.4	84.2	**78.6**	14.9	0.1
56	38.4	87.8	202.7	206.8	**371.4**	16.1	0.5	0.0
62	28.4	51.2	162.7	**697.2**	11.6	0.1	0.0	0.0
68	21.0	**180.8**	**765.4**	1.7	0.1	0.0	0.0	0.0

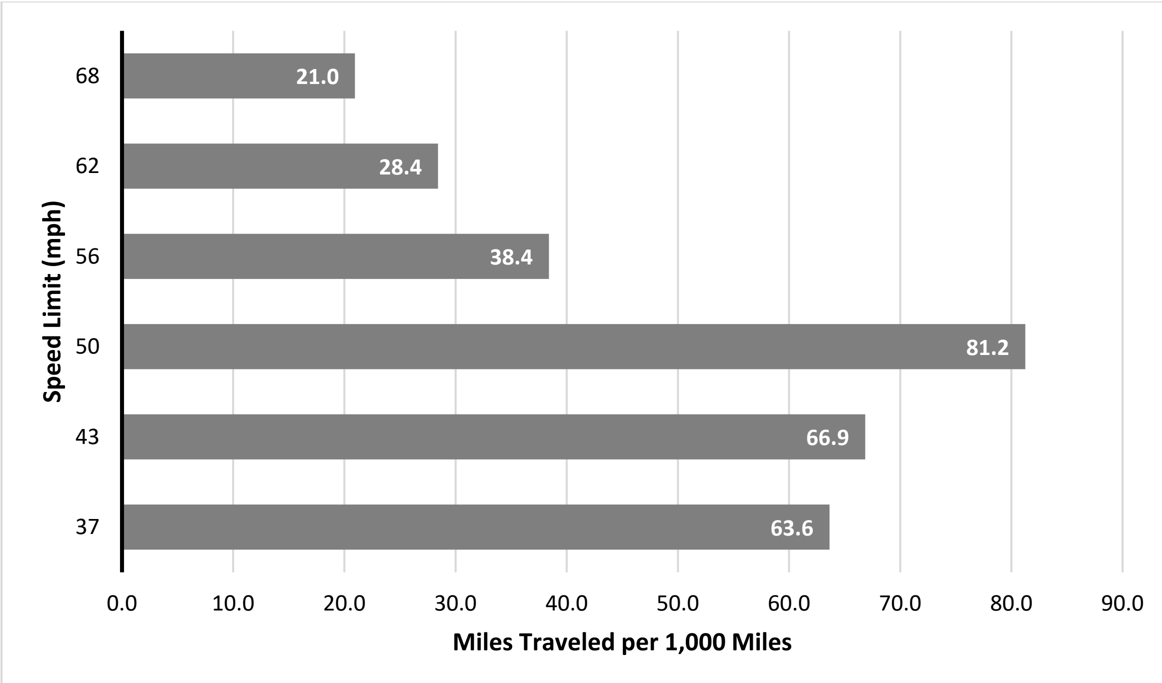

Figure E-2. Chart. Highway miles traveled (per 1,000 miles traveled) in 6 speed limit Canada ODDs for speed behavior type 1: 15 to 10 mph below limit.

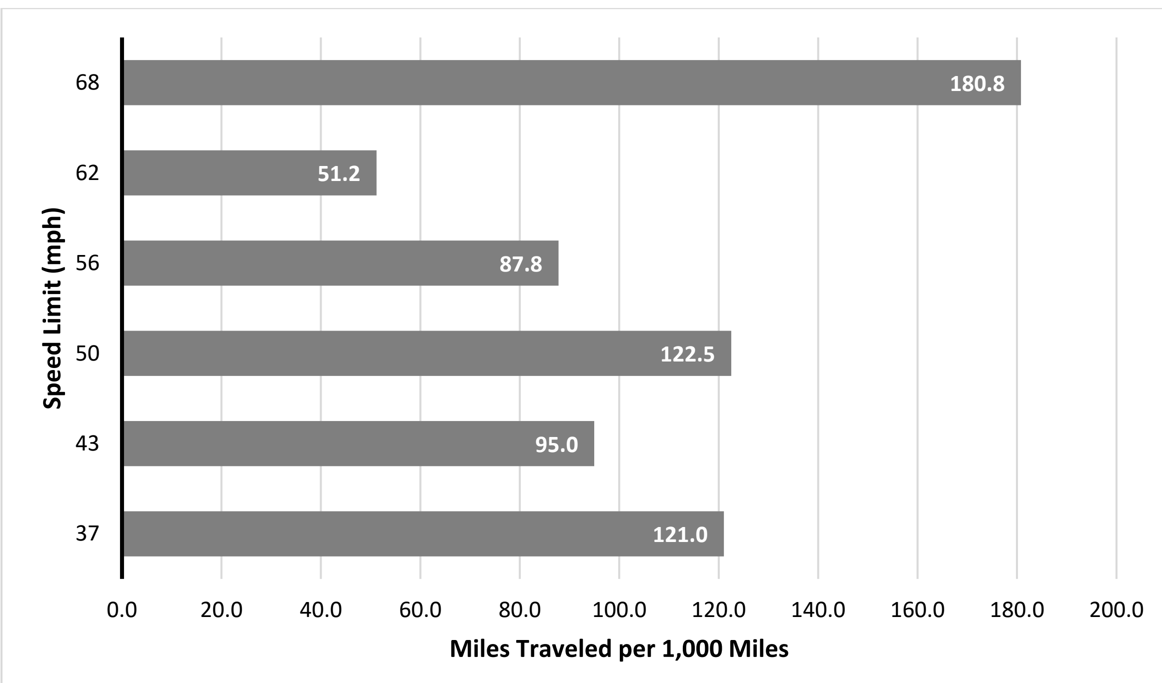

Figure E-3. Chart. Highway miles traveled (per 1,000 miles traveled) in 6 speed limit Canada ODDs for speed behavior type 2: 10 to 5 mph below limit.

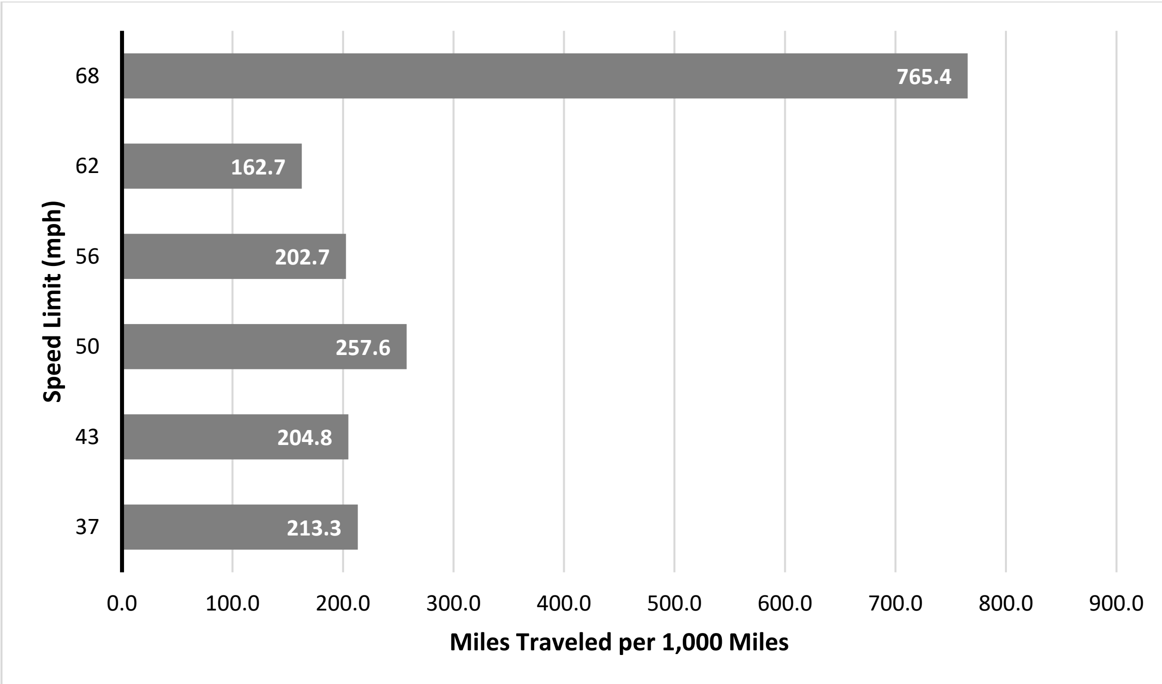

Figure E-4. Chart. Highway miles traveled (per 1,000 miles traveled) in 6 speed limit Canada ODDs for speed behavior type 3: 5 mph below limit to limit.

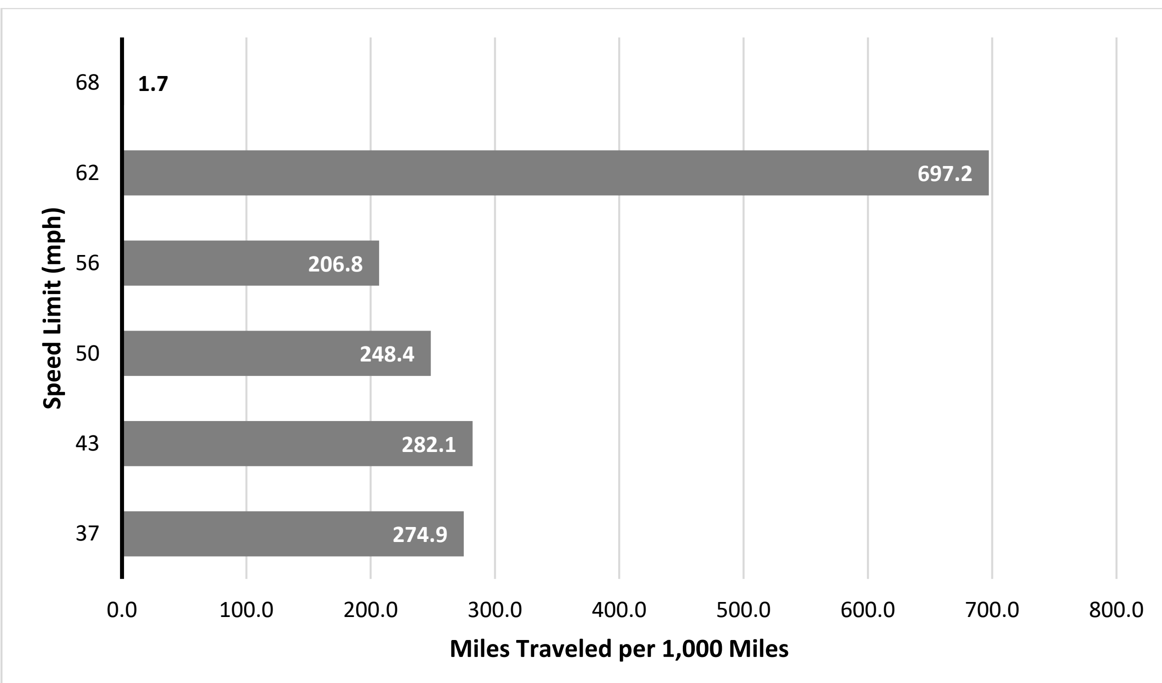

Figure E-5. Chart. Highway miles traveled (per 1,000 miles traveled) in 6 speed limit Canada ODDs for speed behavior type 4: limit to 5 mph above limit.

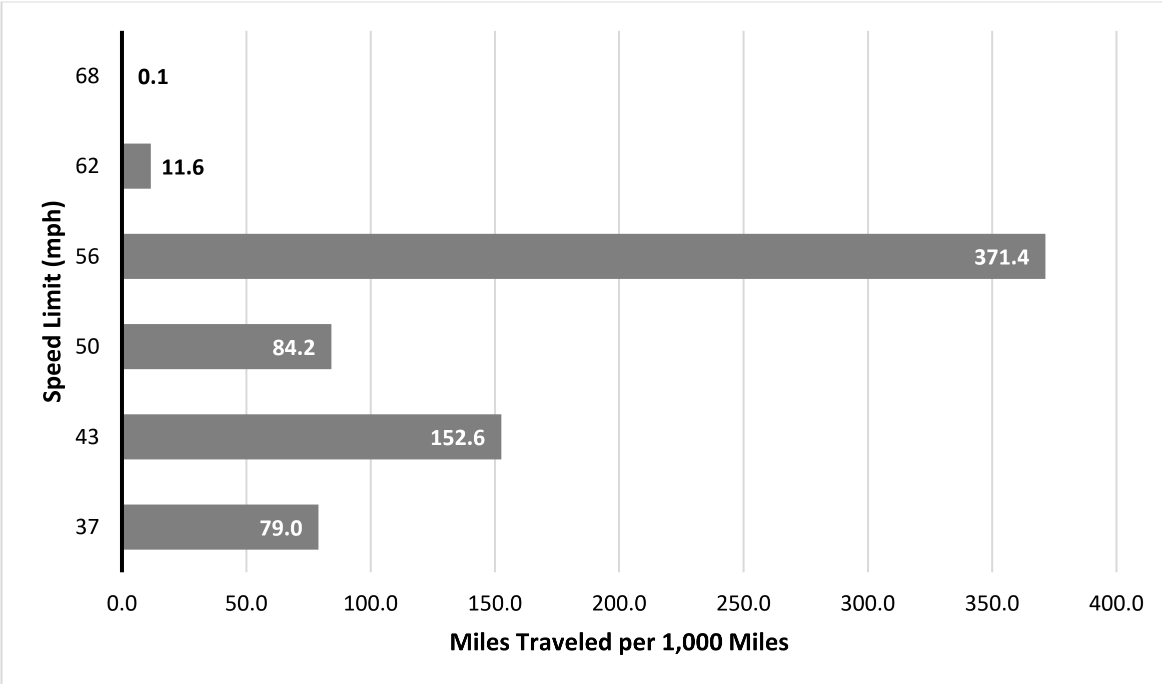

Figure E-6. Chart. Highway miles traveled (per 1,000 miles traveled) in 6 speed limit Canada ODDs for speed behavior type 5: 5 to 10 mph above limit.

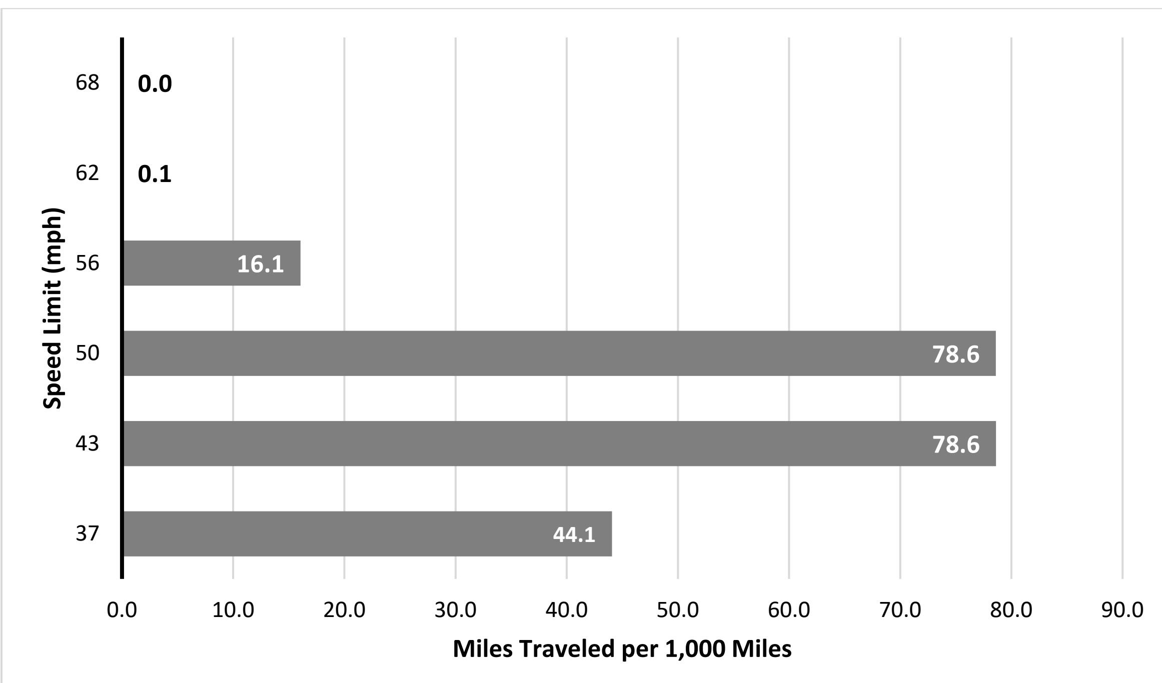

Figure E-7. Chart. Highway miles traveled (per 1,000 miles traveled) in 6 speed limit Canada ODDs for speed behavior type 6: 10 to 15 mph above limit.

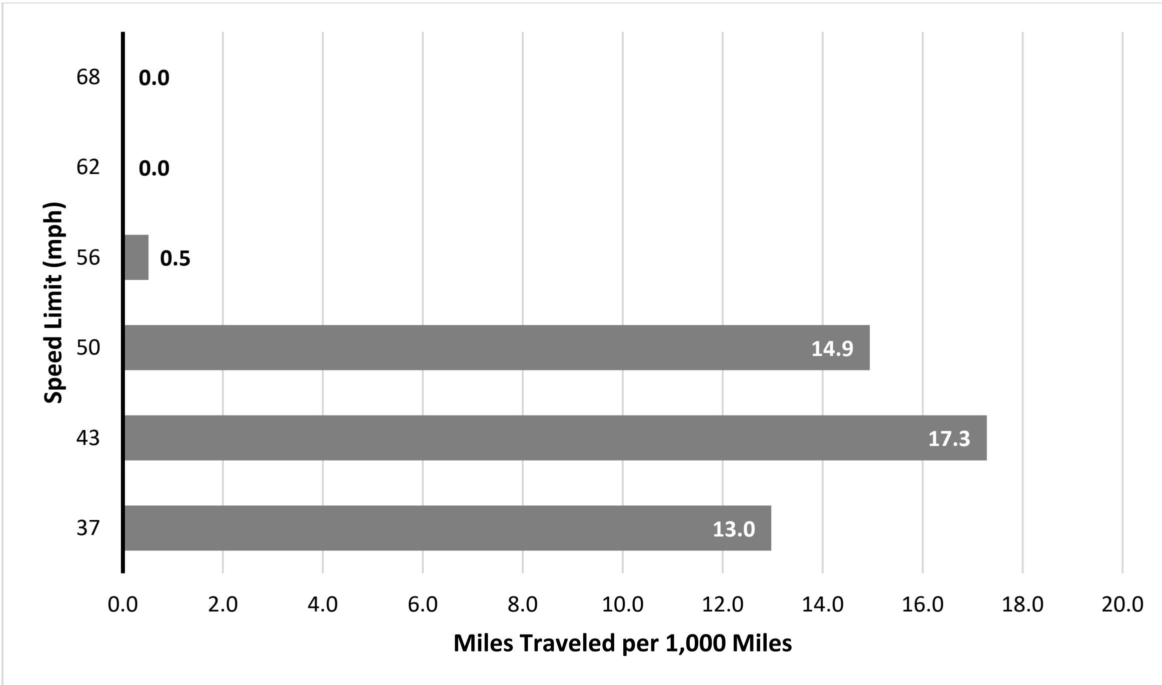

Figure E-8. Chart. Highway miles traveled (per 1,000 miles traveled) in 6 speed limit Canada ODDs for speed behavior type 7: 15 to 20 mph above limit.

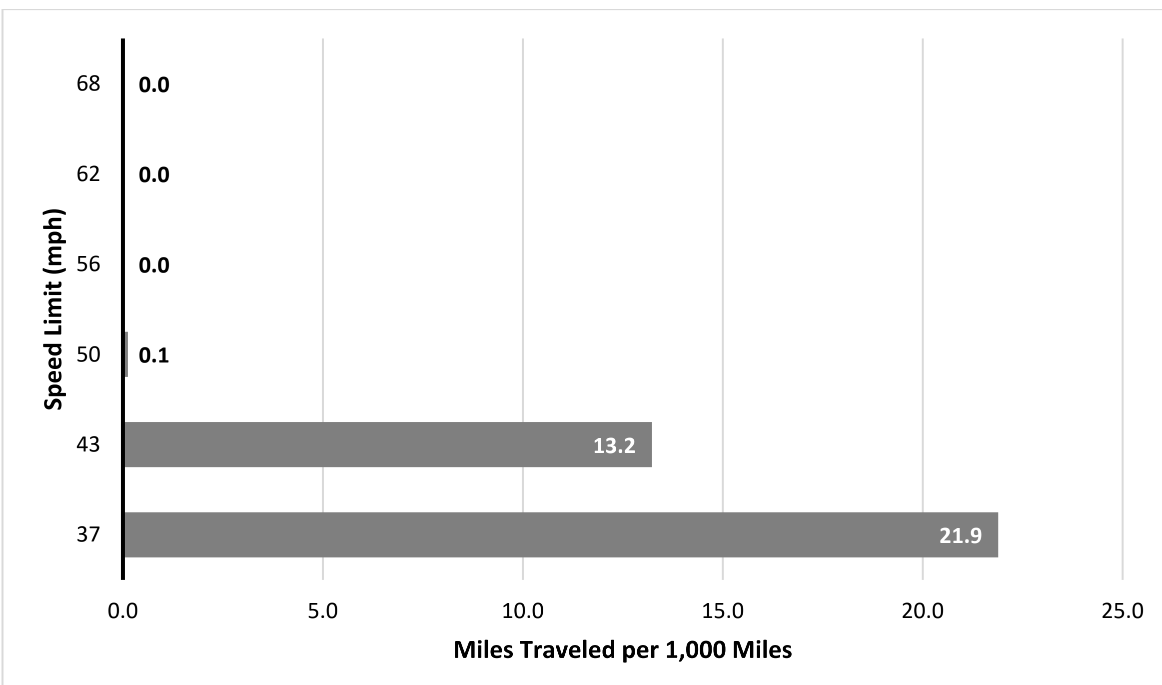

Figure E-9. Chart. Highway miles traveled (per 1,000 miles traveled) in 6 speed limit Canada ODDs for speed behavior type 8: 20 mph or more above limit.

Speed Behavior by Number of Lane ODDs

Table E-6. Highway miles traveled per 1,000 miles exposure for each type of speeding behavior compared by the available number of lanes in Canada.

Number of Lanes Canada ODD	Type 1 (15 to 10 mph below limit)	Type 2 (10 to 5 mph below limit)	Type 3 (5 mph below limit to limit)	Type 4 (limit to 5 mph above limit)	Type 5 (5 to 10 mph above limit)	Type 6 (10 to 15 mph above limit)	Type 7 (15 to 20 mph above limit)	Type 8 (Over 20 mph above limit)
1	23.7	47.9	167.2	**560.4**	**151.5**	7.6	1.0	0.6
2	26.4	**162.7**	**649.8**	102.8	15.2	3.2	0.5	0.3
3	**73.0**	125.2	288.4	234.8	52.5	**19.6**	2.4	1.0
4	65.4	136.7	379.9	196.6	24.4	8.9	**2.6**	**1.0**

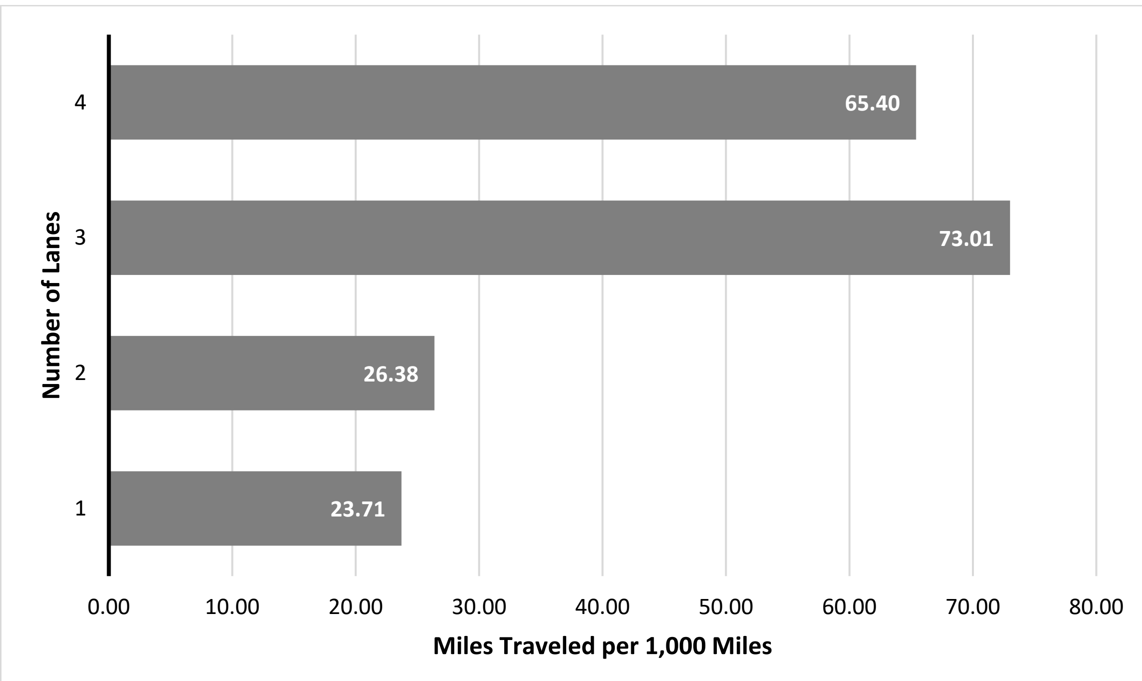

Figure E-10. Chart. Highway miles traveled (per 1,000 miles traveled) by number of lanes in Canada for speed behavior type 1: 15 to 10 mph below limit.

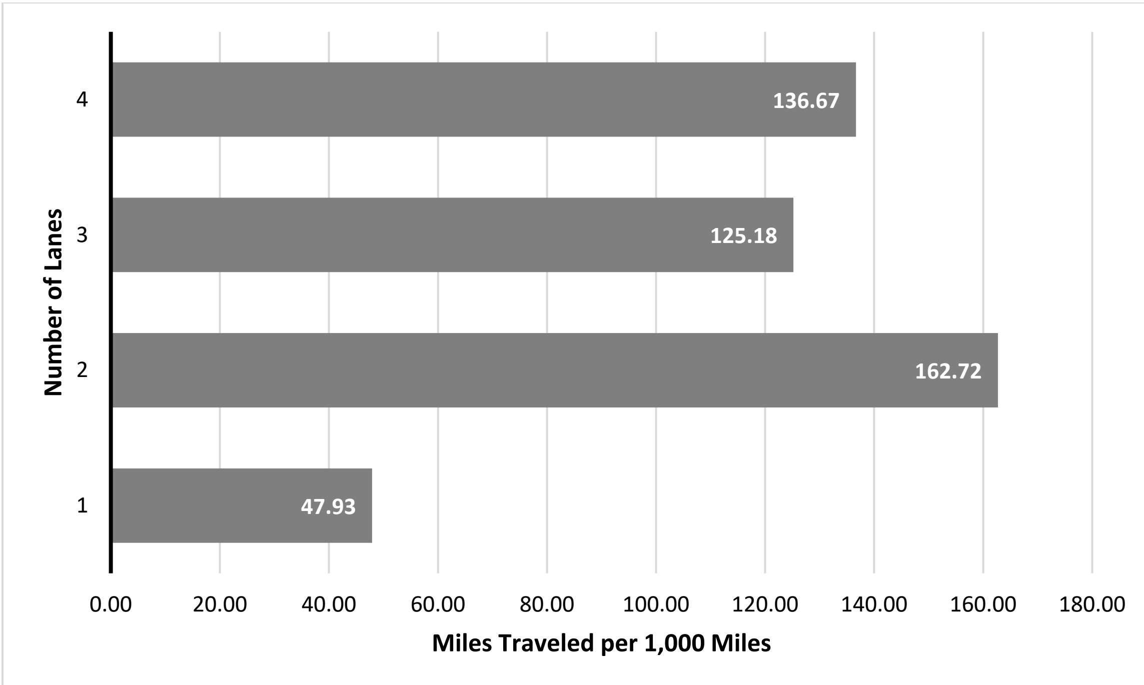

Figure E-11. Chart. Highway miles traveled (per 1,000 miles traveled) by number of lanes in Canada for speed behavior type 2: 10 to 5 mph below limit.

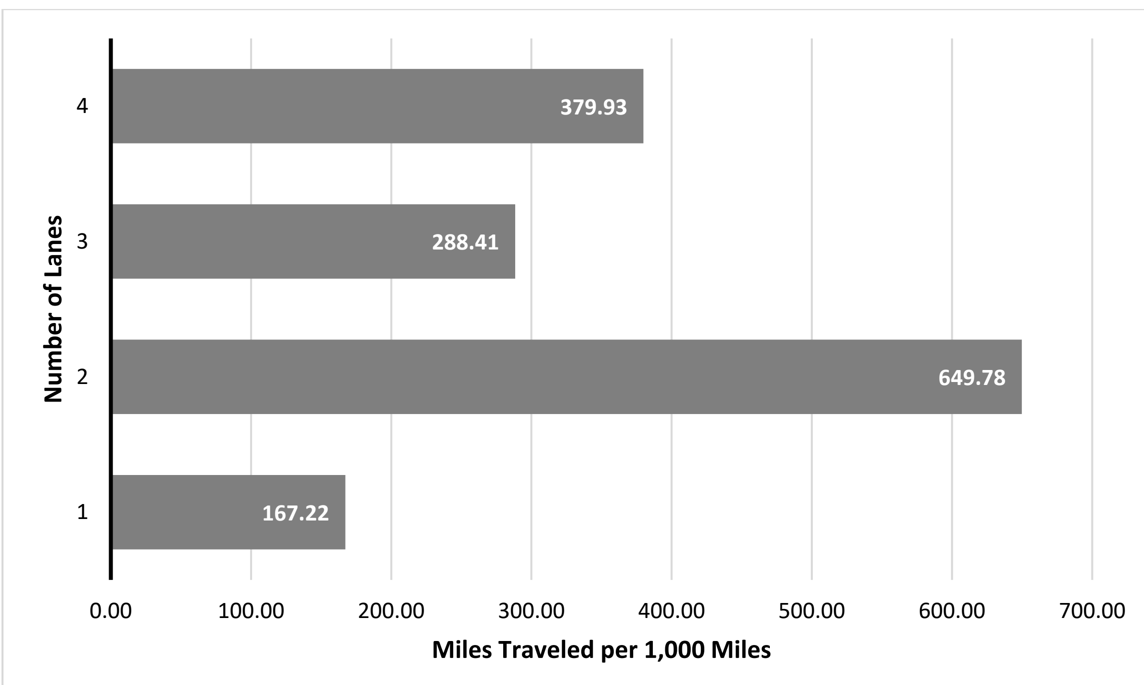

Figure E-12. Chart. Highway miles traveled (per 1,000 miles traveled) by number of lanes in Canada for speed behavior type 3: 5 mph below limit to limit.

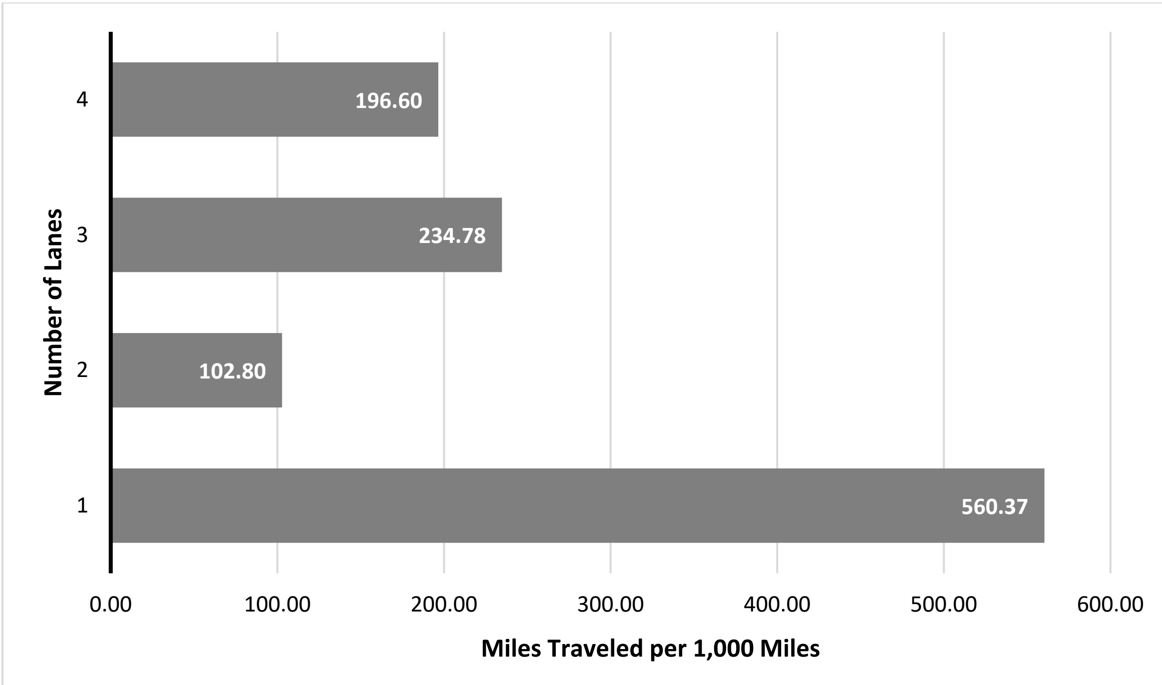

Figure E-13. Chart. Highway miles (per 1,000 miles traveled) by number of lanes in Canada for speed behavior type 4: limit to 5 mph above limit.

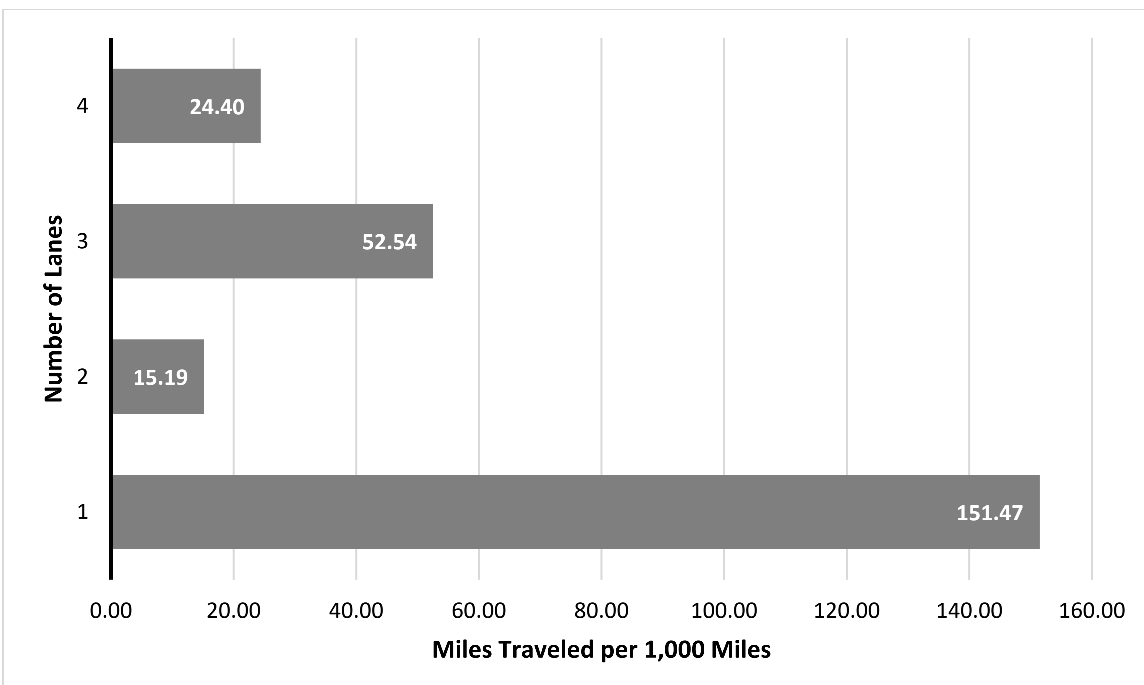

Figure E-14. Chart. Highway miles (per 1,000 miles traveled) by number of lanes in Canada for speed behavior type 5: 5 to 10 mph above limit.

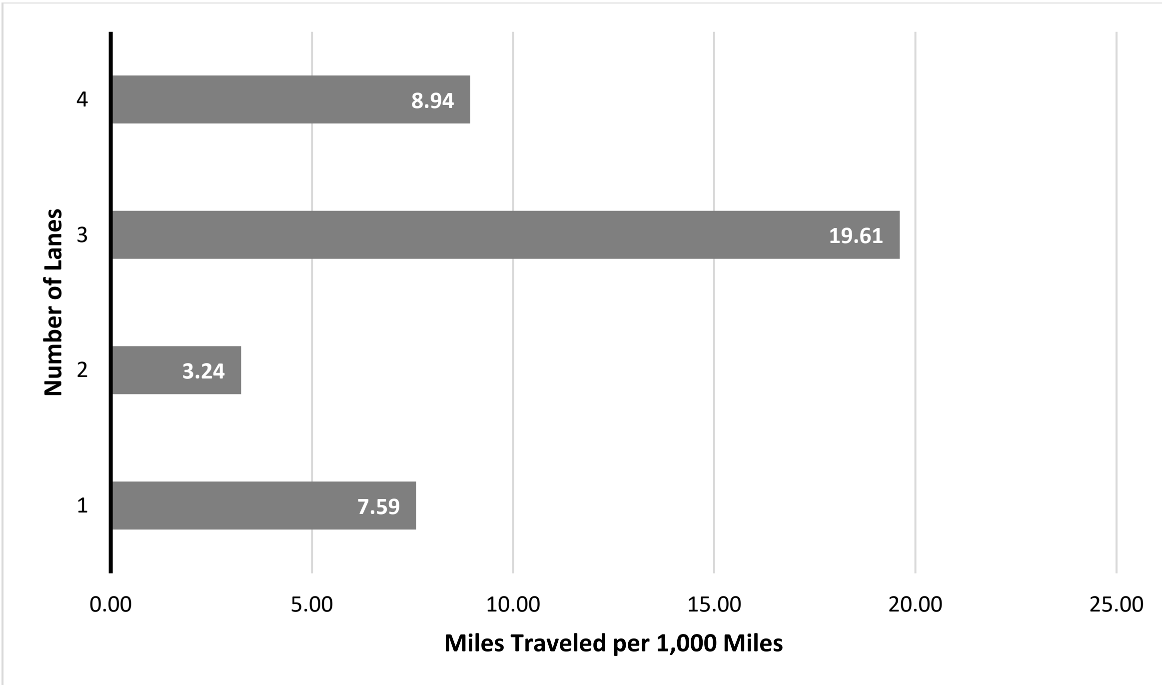

Figure E-15. Chart. Highway miles (per 1,000 miles traveled) by number of lanes in Canada for speed behavior type 6: 10 to 15 mph above limit.

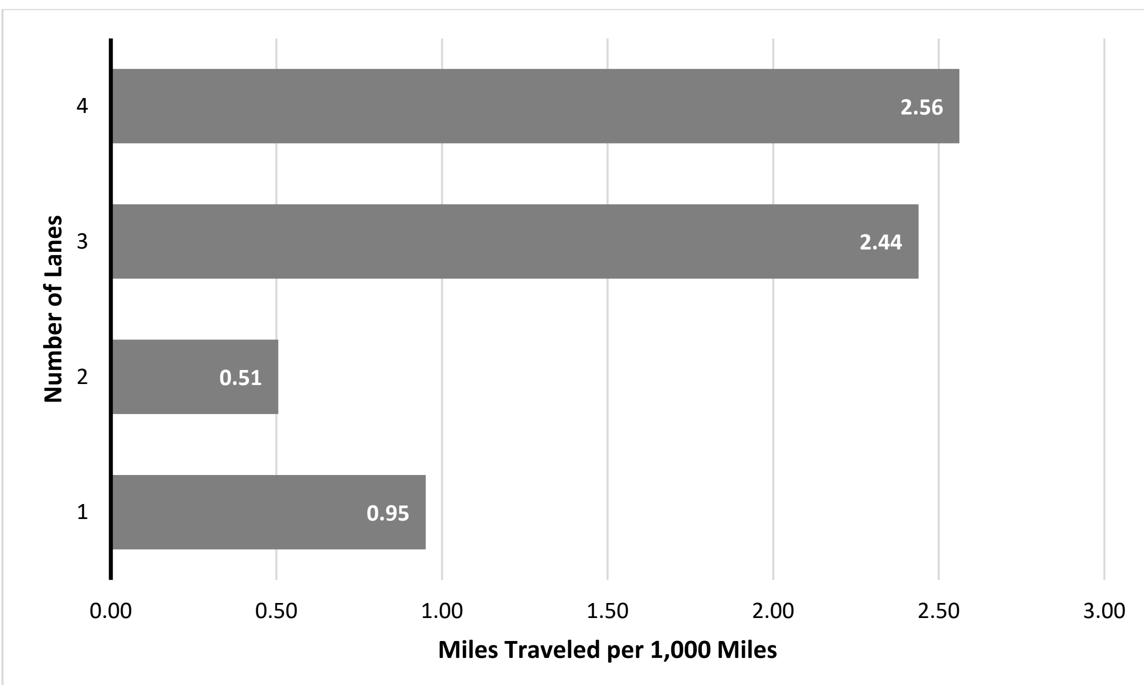

Figure E-16. Chart. Highway miles (per 1,000 miles traveled) by number of lanes in Canada for speed behavior type 7: 15 to 20 mph above limit.

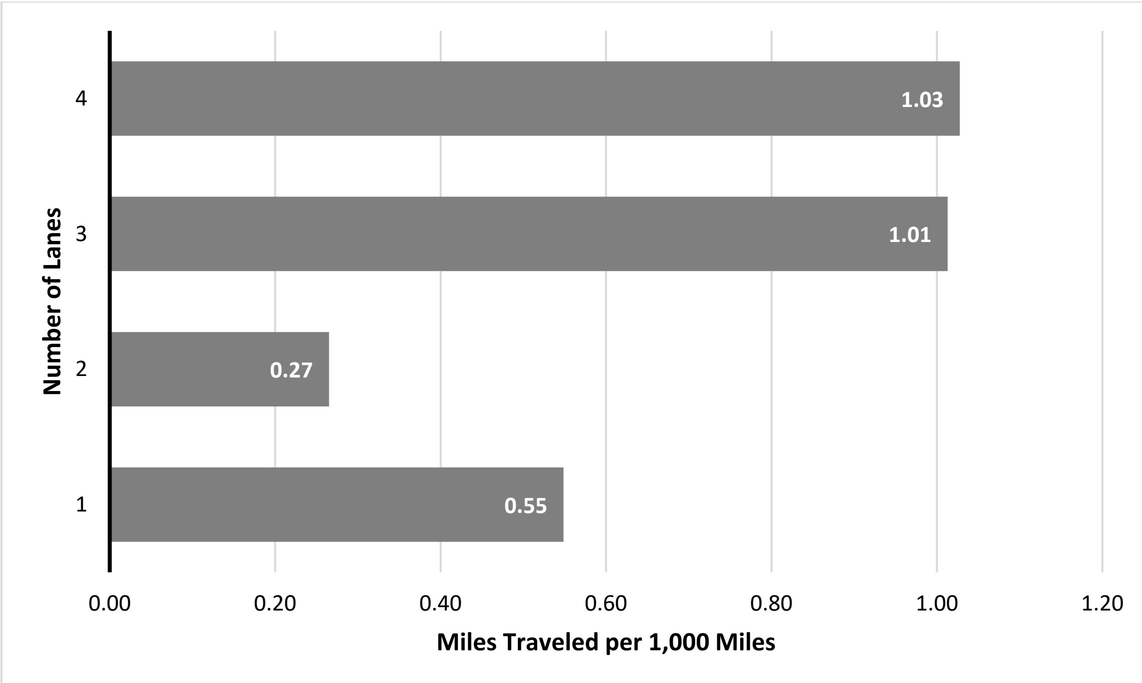

Figure E-17. Chart. Highway miles (per 1,000 miles traveled) by number of lanes in Canada for speed behavior type 8: 20 mph or more above limit.

LATERAL ACCELERATION LEFT/RIGHT

The following section presents the rates of lateral acceleration cases in the Canada dataset. Lateral acceleration is defined by four features calculated from the lateral axis of the accelerometer signal in each link ID, including both left and right (negative/positive) directions.

- All: speed limit ≥ 37 mph, mean acceleration > 0
- Type 1: starting speed ≥ 40 mph, mean acceleration > 0, vehicle lateral acceleration between 0.1 g (inclusive) and 0.2 g
- Type 2: starting speed ≥ 40 mph, mean acceleration > 0, vehicle lateral acceleration between 0.2 g (inclusive) and 0.3 g
- Type 3: starting speed ≥ 40 mph, mean acceleration > 0, vehicle lateral acceleration between 0.3 g (inclusive) and 0.35 g
- Type 4: starting speed ≥ 40 mph, mean acceleration > 0, vehicle lateral acceleration greater than 0.35 g (inclusive)

The data are presented for all highways (one single highway ODD), six different speed limit ODDs, and four number of lane ODDs.

Lateral Acceleration by Highway ODD

Table E-7. Rate of lateral acceleration cases per 1,000 miles exposure in each lateral acceleration type for HW ODD in Canada.

Canada Highway ODD	Type 1 (0.1 g to 0.2 g)	Type 2 (0.2 g to 0.3 g)	Type 3 (0.3 g to 0.35 g)	Type 4 (greater than or equal to 0.35 g)
ALL HW	340.1	12.3	0.4	0.2

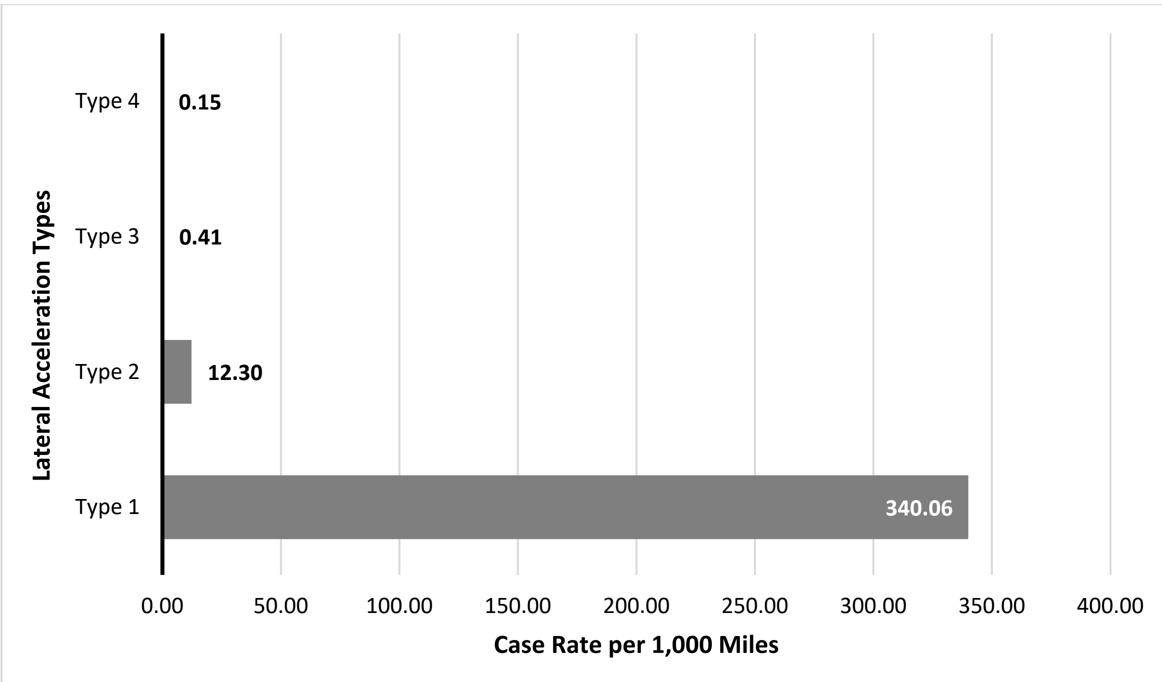

Figure E-18. Chart. A comparison of case frequency rates on Canada highway ODD for lateral acceleration (per 1,000 miles traveled).

Lateral Acceleration by Speed Limit ODDs

Table E-8. Rate of lateral acceleration cases per 1,000 miles exposure in each speed limit ODD for each type of lateral acceleration in Canada.

Speed Limit Canada ODD (mph)	Type 1 (0.1 g to 0.2 g)	Type 2 (0.2 g to 0.3 g)	Type 3 (0.3 g to 0.35 g)	Type 4 (greater than or equal to 0.35 g)
37	303.0	11.2	0.8	0.8
43	**810.5**	**117.2**	2.0	0.5
50	707.4	43.3	**2.7**	**1.7**
56	631.9	37.7	1.2	0.2
62	336.7	8.4	0.3	0.1

Speed Limit Canada ODD (mph)	Type 1 (0.1 g to 0.2 g)	Type 2 (0.2 g to 0.3 g)	Type 3 (0.3 g to 0.35 g)	Type 4 (greater than or equal to 0.35 g)
68	257.1	5.1	0.2	0.1

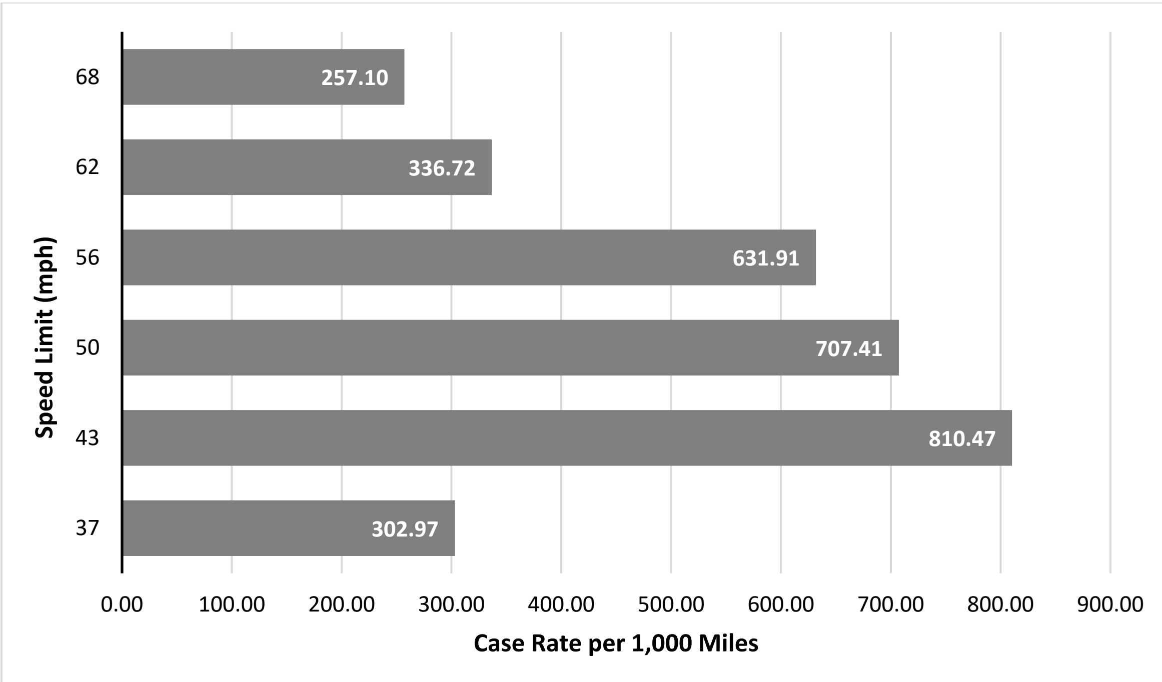

Figure E-19. Chart. Case frequency in six speed limit Canada ODDs for lateral acceleration type 1: 0.1 g to 0.2 g (per 1,000 miles traveled).

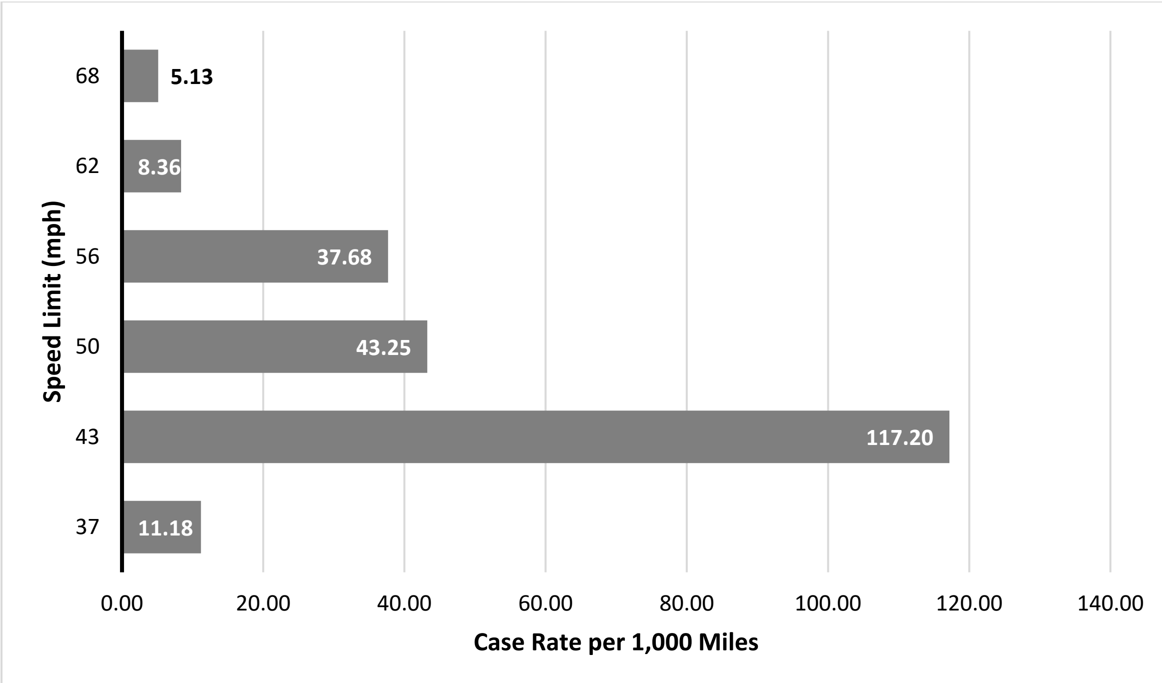

Figure E-20. Chart. Case frequency in six speed limit Canada ODDs for lateral acceleration type 2: 0.2 g to 0.3 g (per 1,000 miles traveled).

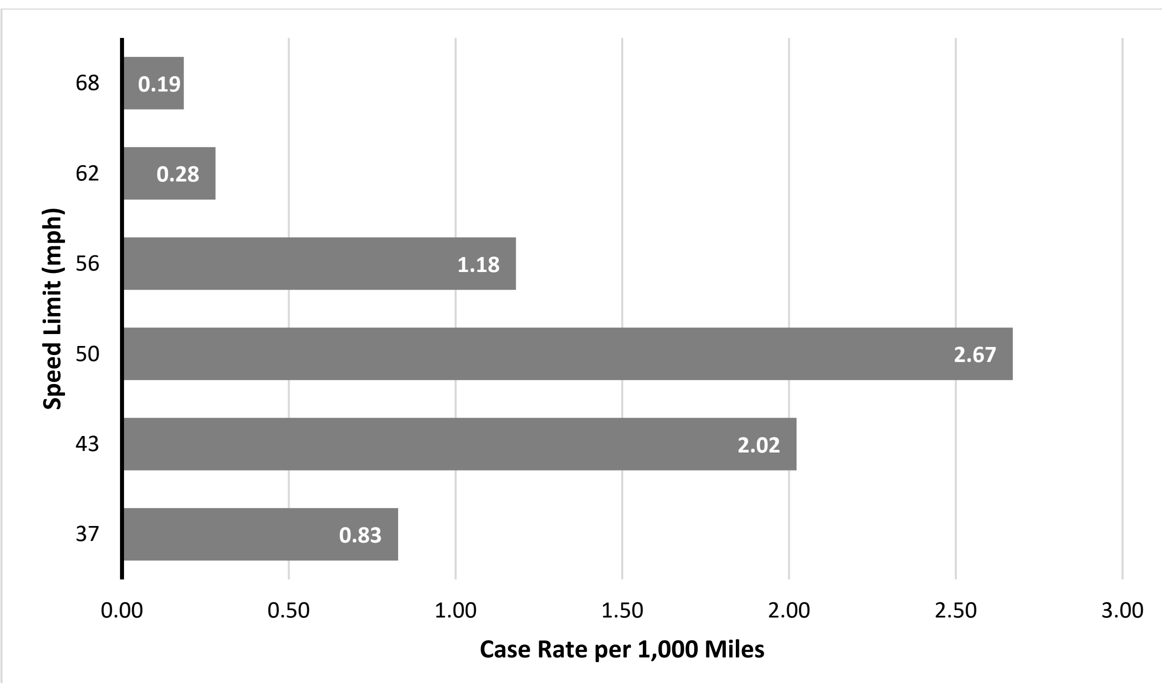

Figure E-21. Chart. Case frequency in six speed limit Canada ODDs for lateral acceleration type 3: 0.3 g to 0.35 g (per 1,000 miles traveled).

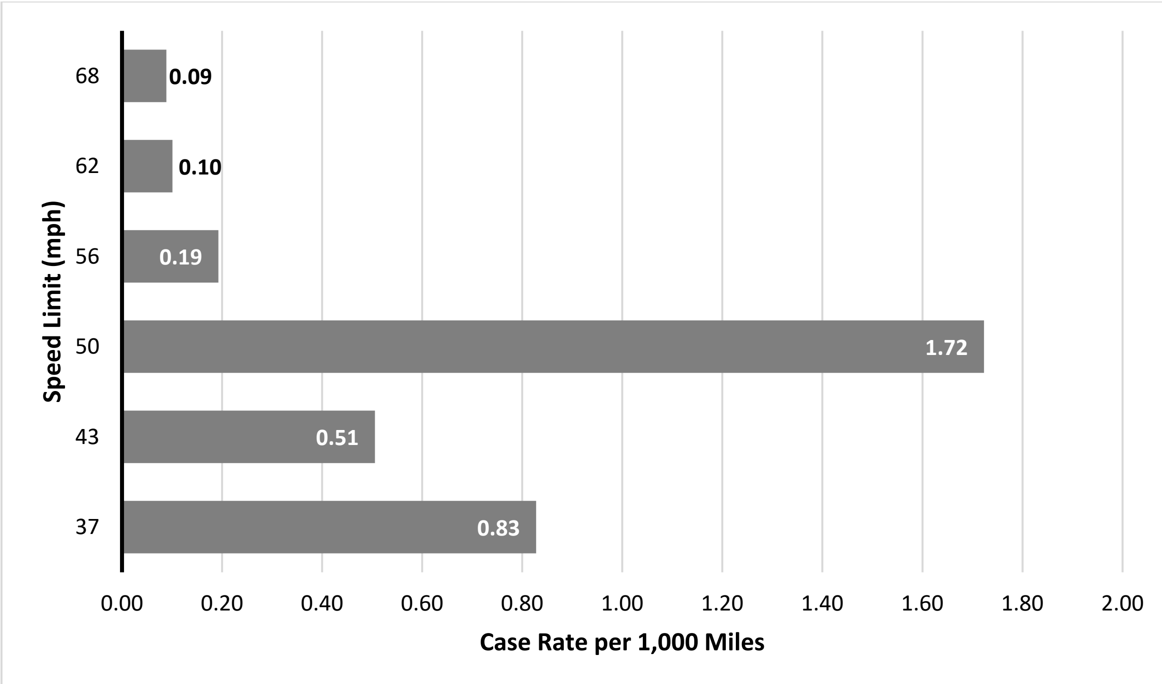

Figure E-22. Chart. Case frequency in six speed limit Canada ODDs for lateral acceleration type 4: greater than or equal to 0.35 g (per 1,000 miles traveled).

Lateral Acceleration by Number of Lane ODDs

Table E-9. Case Rate per 1,000 miles exposure for each type of lateral acceleration compared by the available number of lanes in Canada.

Number of Lanes Canada ODD	Type 1 (0.1 g to 0.2 g)	Type 2 (0.2 g to 0.3 g)	Type 3 (0.3 g to 0.35 g)	Type 4 (greater than or equal to 0.35 g)
1	224.8	19.5	0.9	0.1
2	154.9	6.1	0.2	0.1
3	875.8	**201.6**	2.0	0.9
4	**1,731.8**	107.7	**5.5**	**1.0**

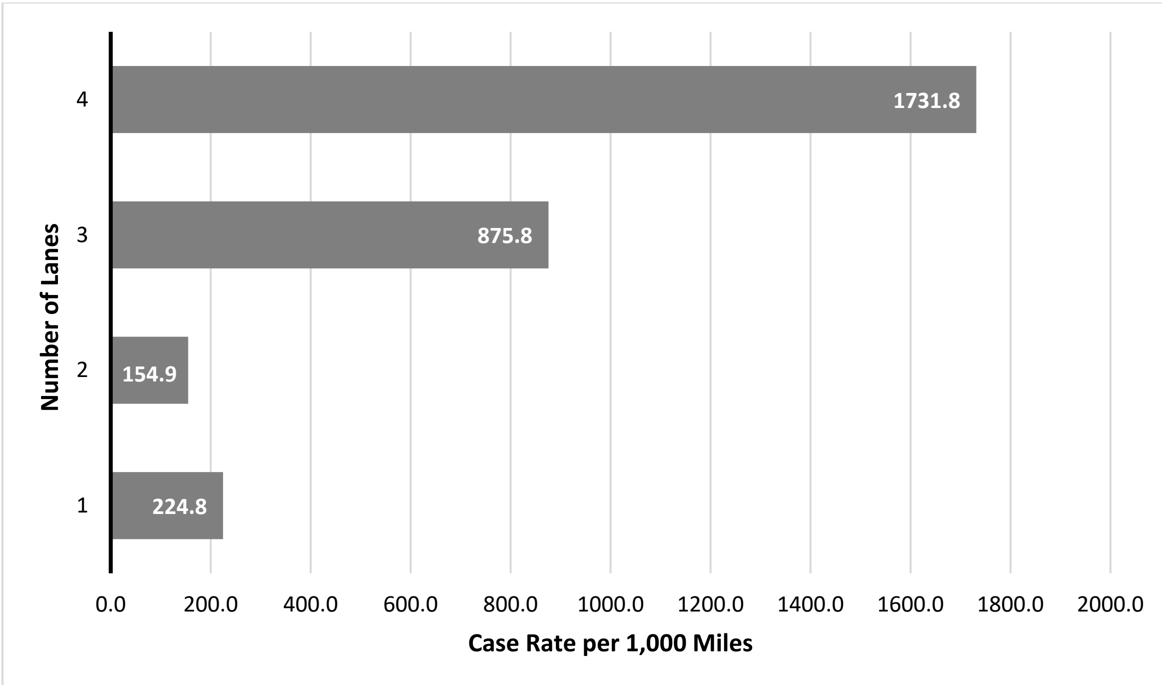

Figure E-23. Chart. Case rate by number of lanes in Canada for lateral acceleration type 1: 0.1 g to 0.2 g (per 1,000 miles traveled).

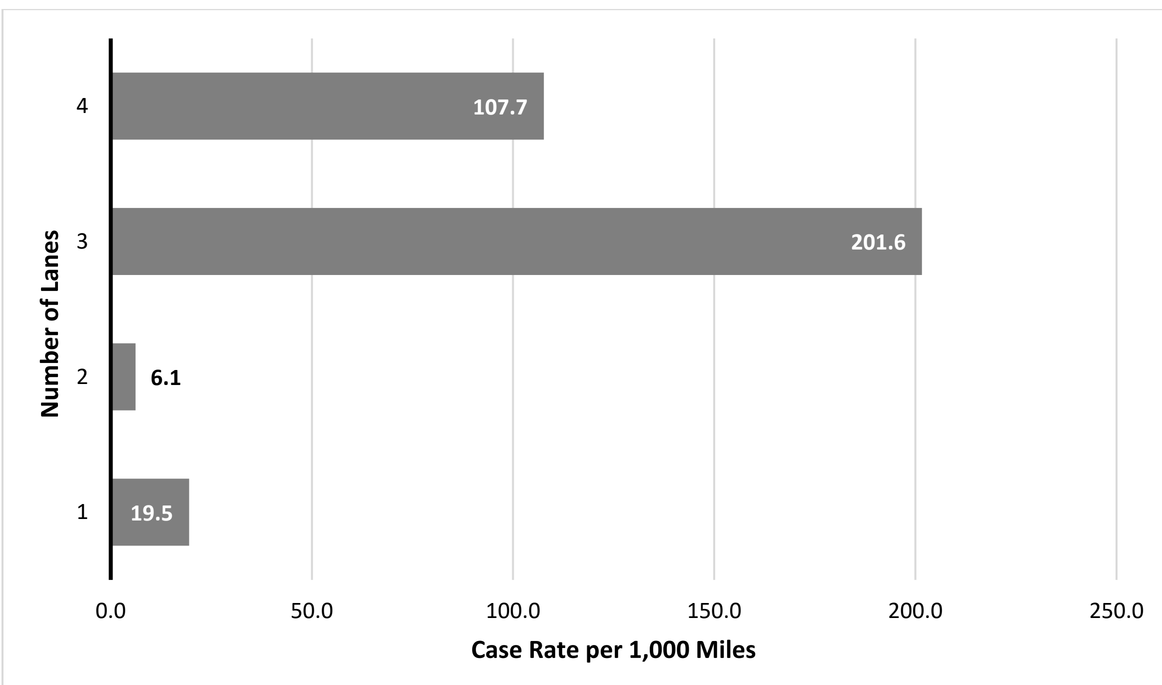

Figure E-24. Chart. Case rate by number of lanes in Canada for lateral acceleration type 2: 0.2 g to 0.3 g (per 1,000 miles traveled).

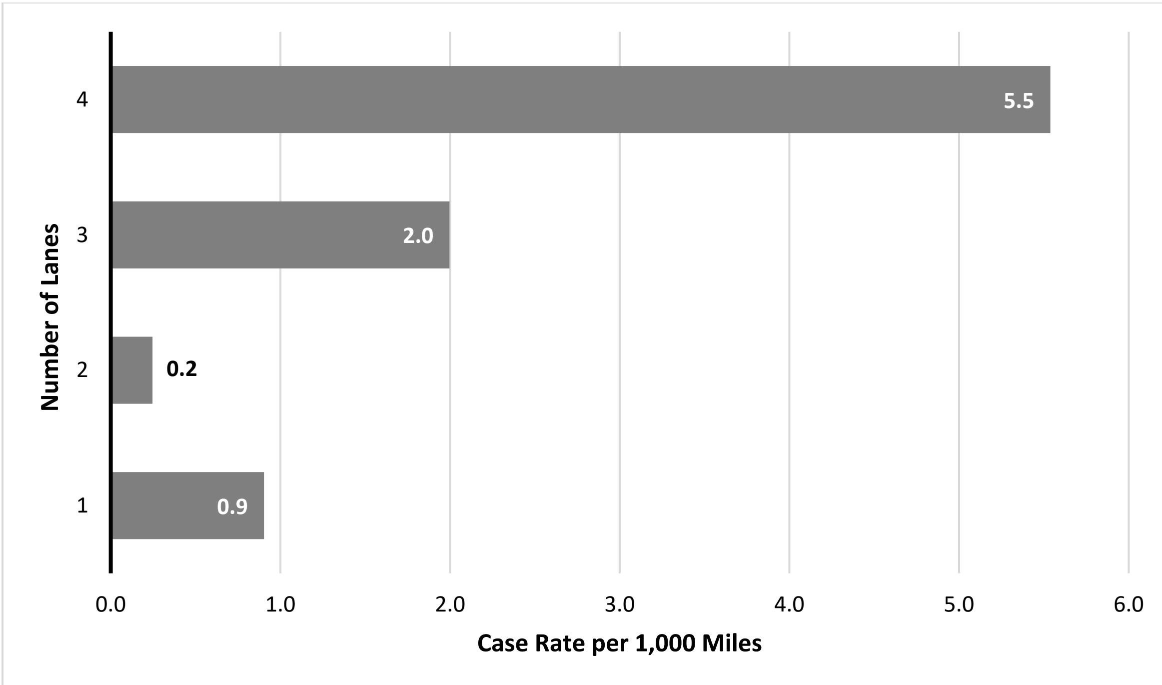

Figure E-25. Chart. Case rate by number of lanes in Canada for lateral acceleration type 3: 0.3 g to 0.35 g (per 1,000 miles traveled).

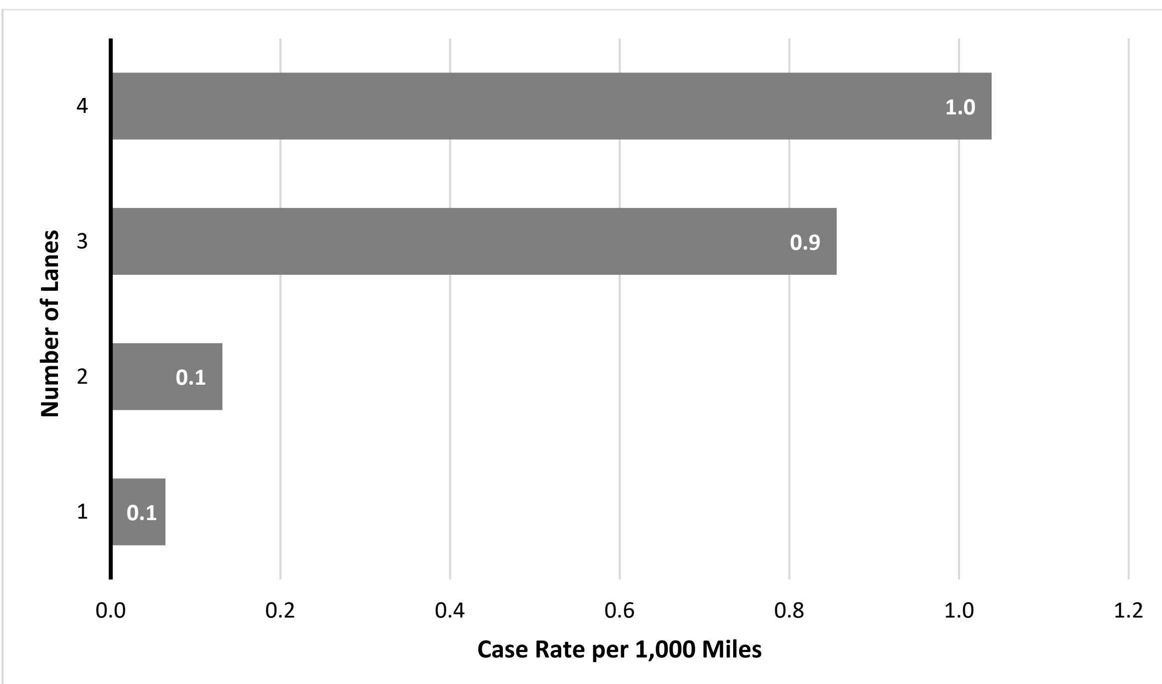

Figure E-26. Chart. Case rate by number of lanes in Canada for lateral acceleration type 4: greater than or equal to 0.35 g (per 1,000 miles traveled).

LONGITUDINAL DECELERATION

The following section presents rates of longitudinal deceleration cases in the Canada dataset. Longitudinal deceleration is defined by three features calculated from the longitudinal axis of the accelerometer signal in each link ID.

- All: speed limit ≥ 37 mph, change in speed > 3 mph
- Type 1: starting speed ≥ 40 mph, change in speed > 3 mph, longitudinal deceleration between 0.1 g and 0.2 g
- Type 2: starting speed ≥ 40 mph, change in speed > 3 mph, longitudinal deceleration between 0.2 g and 0.35 g
- Type 3: starting speed ≥ 40 mph, change in speed > 3 mph, longitudinal deceleration greater than or equal to 0.35 g

The data are presented for all highways (one single highway ODD), six different speed limit ODDs, and four number of lanes ODDs.

Longitudinal Deceleration by Highway ODD

Table E-10. Rate of longitudinal deceleration cases per 1,000 miles exposure in each longitudinal deceleration type in highway ODD for Canada data.

Canada Highway ODD	Type 1 (0.1 g to 0.2 g)	Type 2 (0.2 g to 0.35 g)	Type 3 (greater than or equal to 0.35 g)
ALL HW	34.1	5.8	0.2

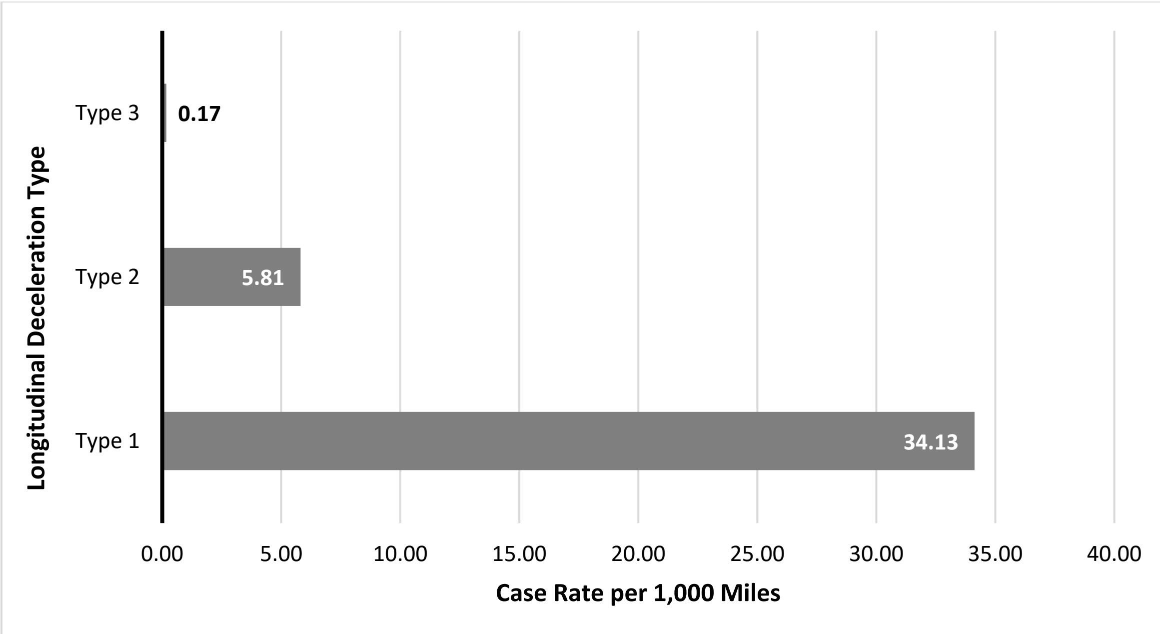

Figure E-27. Chart. Case frequencies in the highway ODD by Canada for all longitudinal deceleration types (per 1,000 miles traveled).

Longitudinal Deceleration by Speed Limit ODDs

Table E-11. Rate of longitudinal deceleration cases per 1,000 miles exposure in each speed limit Canadian ODD for each type of longitudinal deceleration behavior.

Speed Limit Canada ODD (mph)	Type 1 (0.1 g to 0.2 g)	Type 2 (0.2 g to 0.35 g)	Type 3 (greater than or equal to 0.35 g)
37	84.44	23.59	0.62
43	178.78	27.61	**1.21**
50	**213.23**	**31.45**	0.95
56	74.03	15.16	0.39
62	41.19	6.41	0.23
68	12.31	1.96	0.04

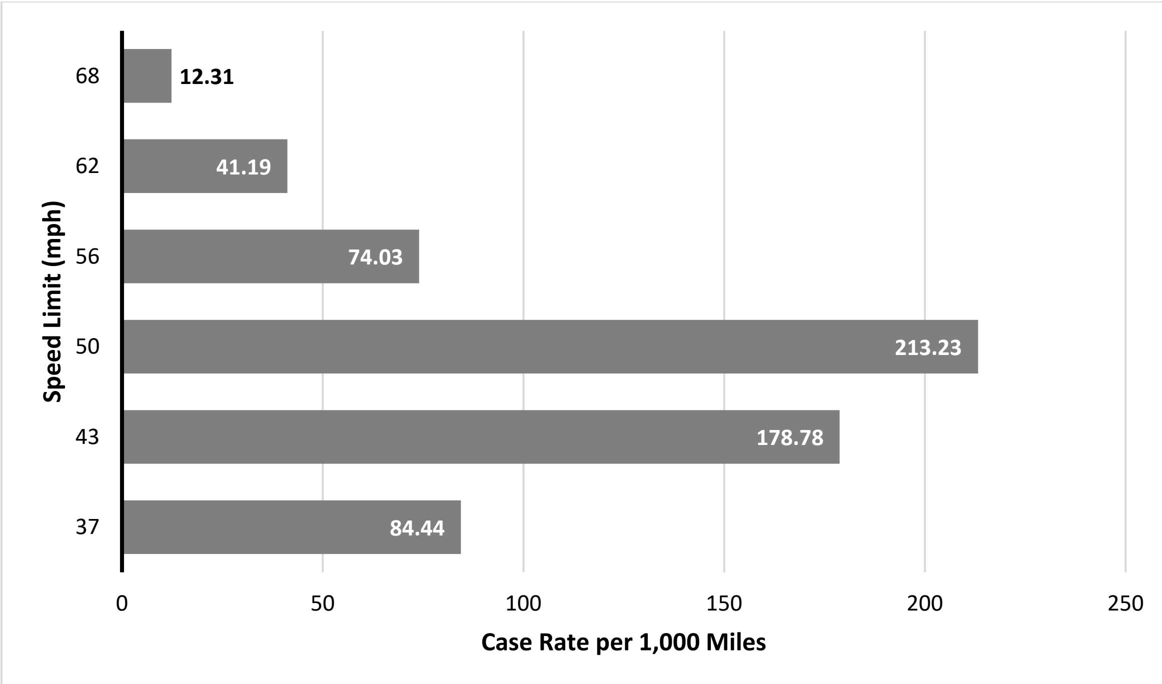

Figure E-28. Chart. Case frequency by speed limit Canadian ODDs for longitudinal deceleration type 1: 0.1 g to 0.2 g (per 1,000 miles traveled).

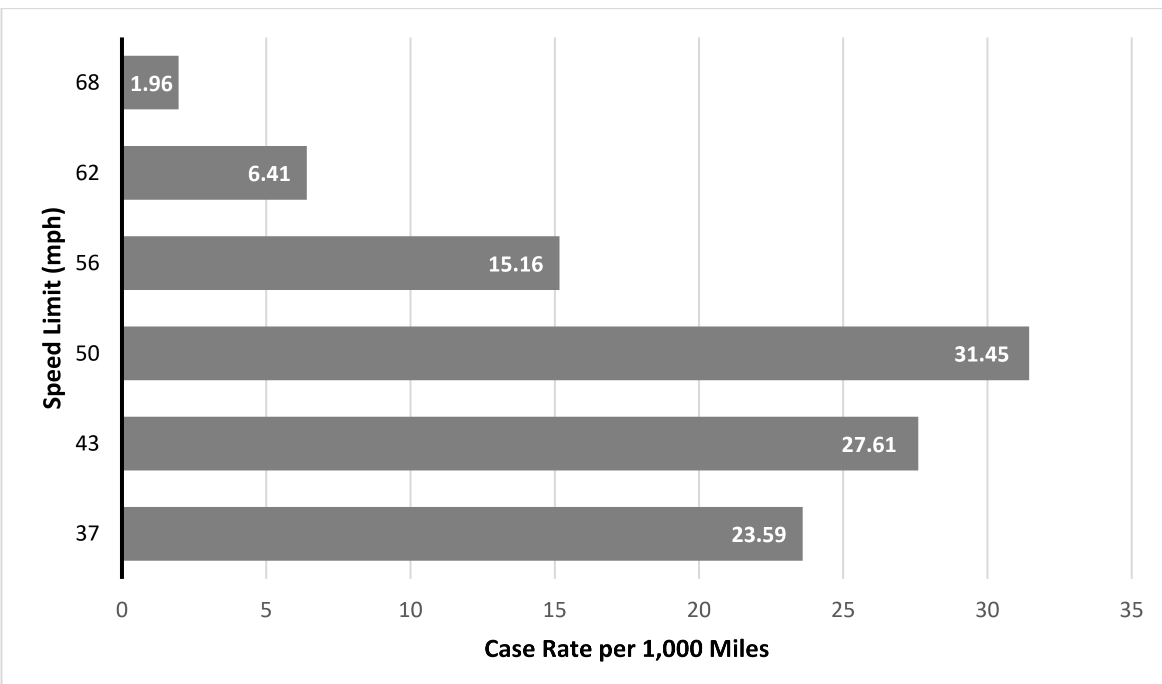

Figure E-29. Chart. Case frequency by speed limit Canadian ODDs for longitudinal deceleration type 2: 0.2 g to 0.35 g (per 1,000 miles traveled).

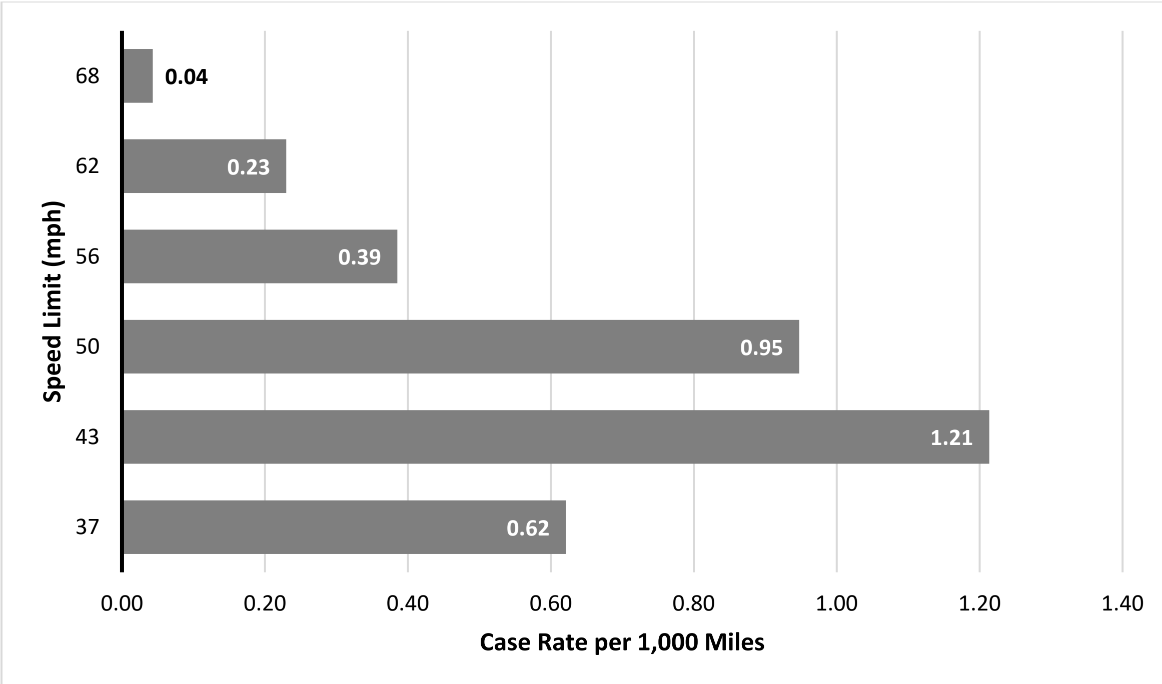

Figure E-30. Chart. Case frequency by speed limit Canadian ODDs for longitudinal deceleration type 3: greater than or equal to 0.35 g (per 1,000 miles traveled).

Longitudinal Deceleration by Number of Lane ODDs

Table E-12. Case rate per 1,000 miles exposure for each type of longitudinal deceleration compared by the available number of lanes in Canada.

Number of Lanes Canada ODD	Type 1 (0.1 g to 0.2 g)	Type 2 (0.2 g to 0.35 g)	Type 3 (greater than or equal to 0.35 g)
1	41.2	16.2	1.4
2	26.4	8.4	0.9
3	256.1	120.2	5.5
4	**598.1**	**279.3**	**10.4**

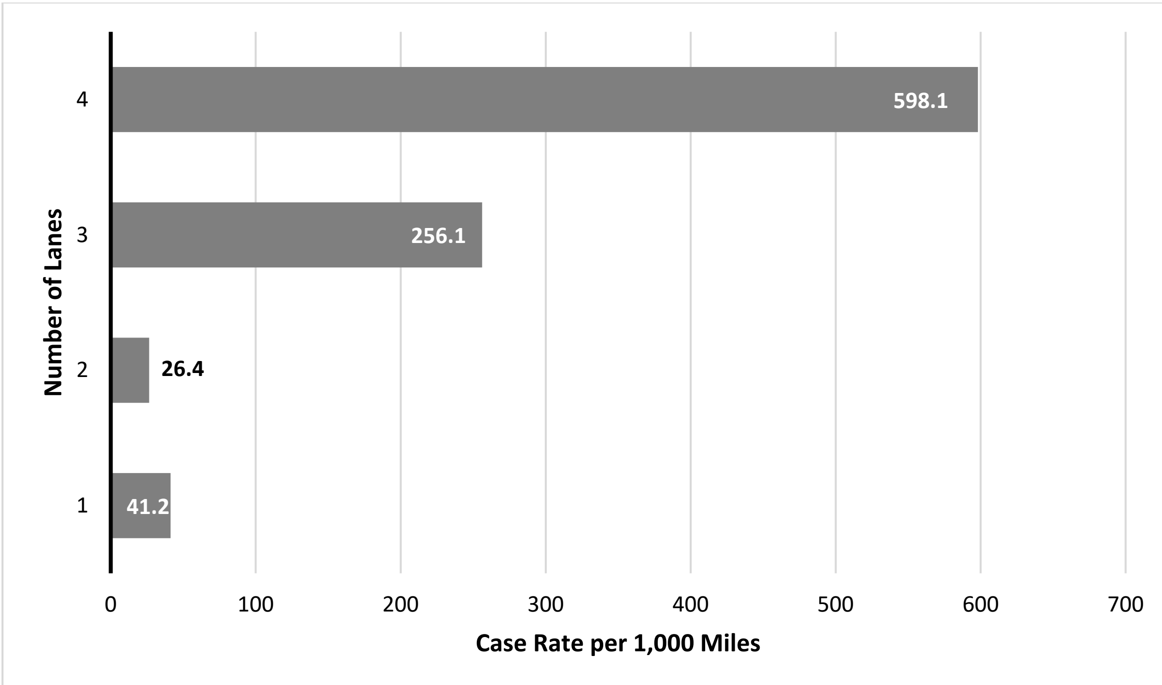

Figure E-31. Chart. Case rates by number of lanes for longitudinal deceleration type 1: 0.1 g to 0.2 g (per 1,000 miles traveled).

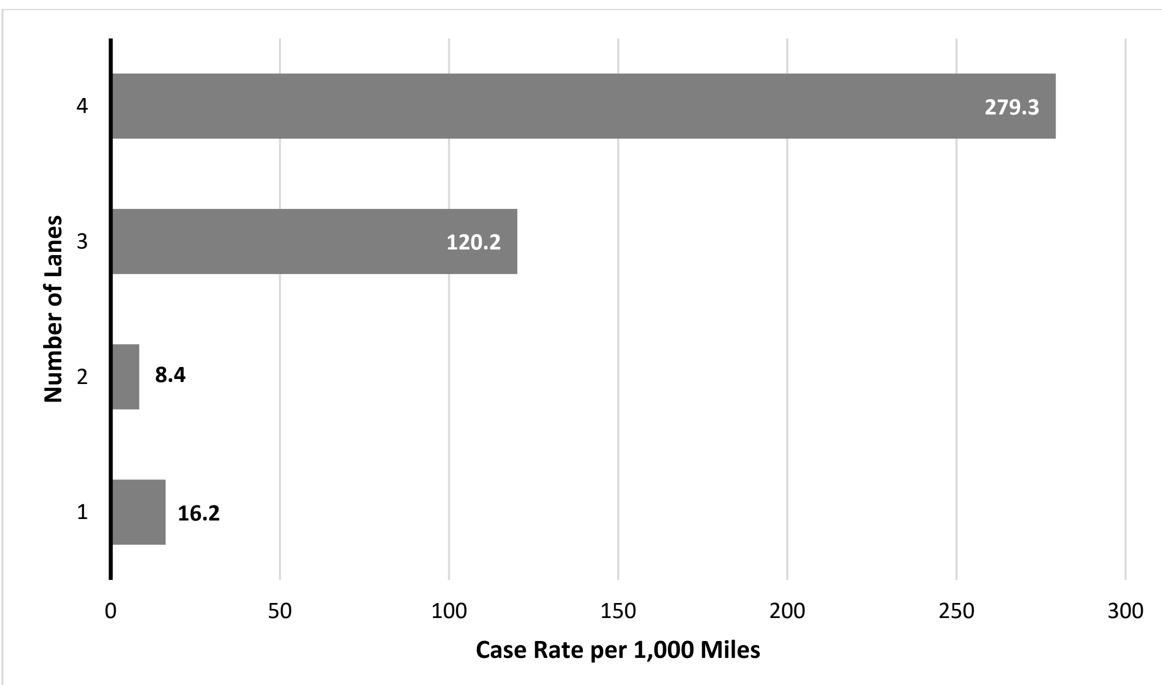

Figure E-32. Chart. Case rates by number of lanes for longitudinal deceleration type 2: 0.2 g to 0.35 g (per 1,000 miles traveled).

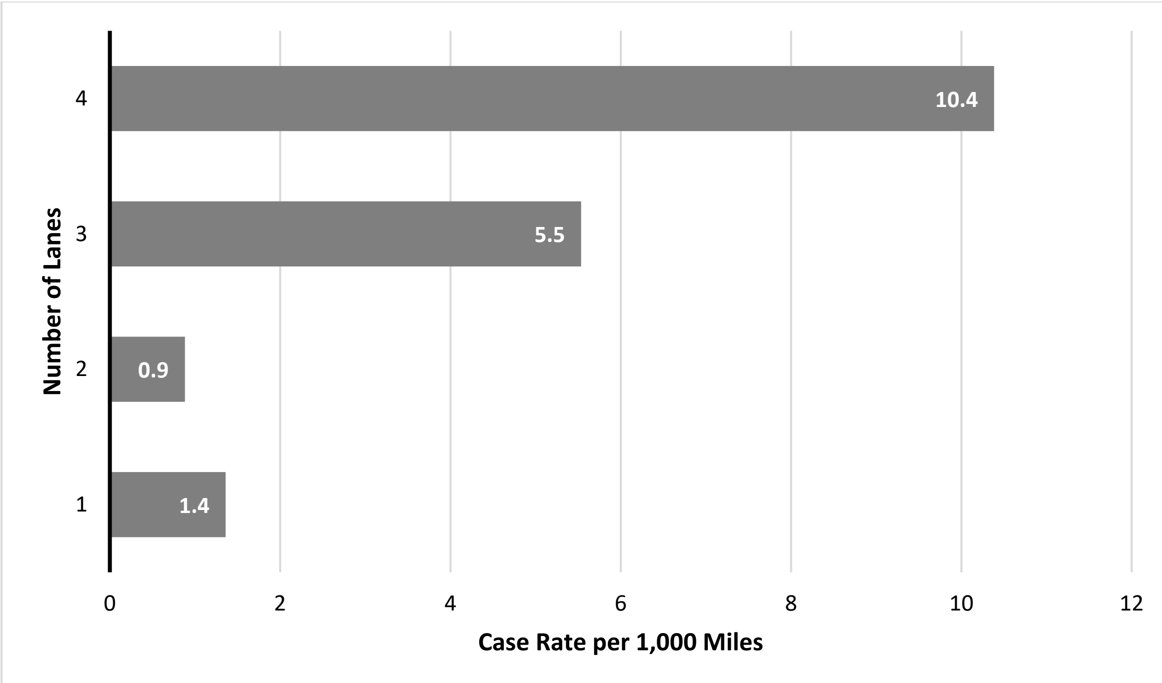

Figure E-33. Chart. Case rates by number of lanes for longitudinal deceleration type 3: greater than or equal to 0.35 g (per 1,000 miles traveled).

Lane Deviation

Lane deviation is defined by four features calculated from the lane offset signal in each link ID.

- All: speed limit ≥ 37 mph
- Type 1, acceptable: deviation 0–21 inches, tires on both sides inside the lane[5]
- Type 2, violation: deviation 21–33 inches, one tire is outside lane 0–12 inches
- Type 3, violation: deviation 33–45 inches, one tire is outside lane 12–24 inches
- Type 4, violation: deviation greater than 45 inches, one tire is more than 24 inches outside the lane

Lane Deviation by Speed Limit

Table E-13 shows the distribution of different lane deviation types seen by different speed limits. As anticipated, the majority of the miles traveled on all highways were type 1, in which the truck was inside the lane markings. Figures E-34 through E-37 compare miles traveled in each deviation category for every 1,000 miles traveled in various speed limit ODDs for lane deviation categories of type 1, type 2, type 3, and type 4, respectively.

[5] As in data collected in the United States, the positioning of the truck relative to lane markings is included for illustration but was not directly measured. The deviation from the centerline was measured precisely, while the position relative to lane markings was calculated based on a lane width of 12 feet and a standard truck width.

Table E-13. Distribution of vehicle miles per 1,000 miles exposure for each type of lane deviation by six speed limit Canadian ODDs.

Speed Limit Canada ODD (mph)	Type 1 (0-21 inches, inside lane)	Type 2 (21-33 inches, outside lane)	Type 3 (33-45 inches, outside lane)	Type 4 (greater than 45 inches, outside lane)
37	957.6	26.6	**6.7**	**9.1**
43	960.9	26.2	5.6	7.3
50	962.4	26.8	5.3	5.5
56	968.7	22.9	3.4	5.0
62	947.0	**41.7**	5.6	5.6
68	**976.3**	20.1	2.4	1.2

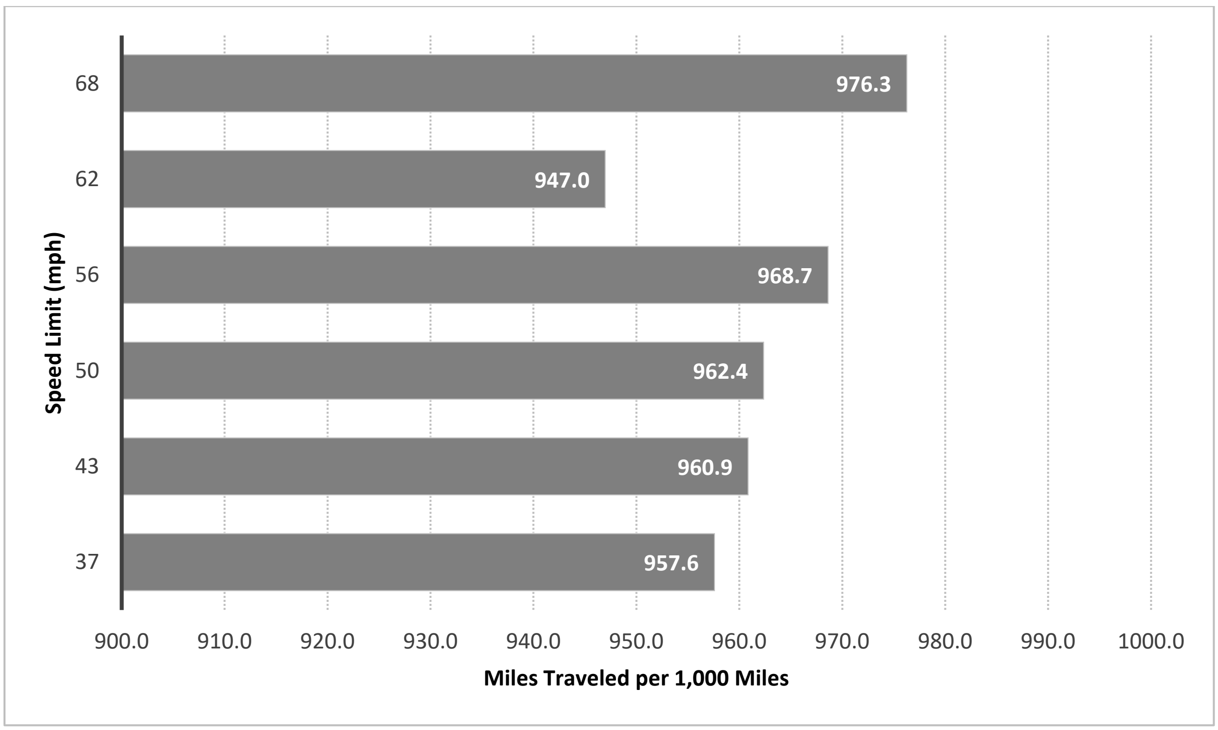

Figure E-34. Chart. Highway miles traveled in different speed limit Canadian ODDs for lane deviation type 1: 0-21 inches, inside lane (per 1,000 miles traveled).

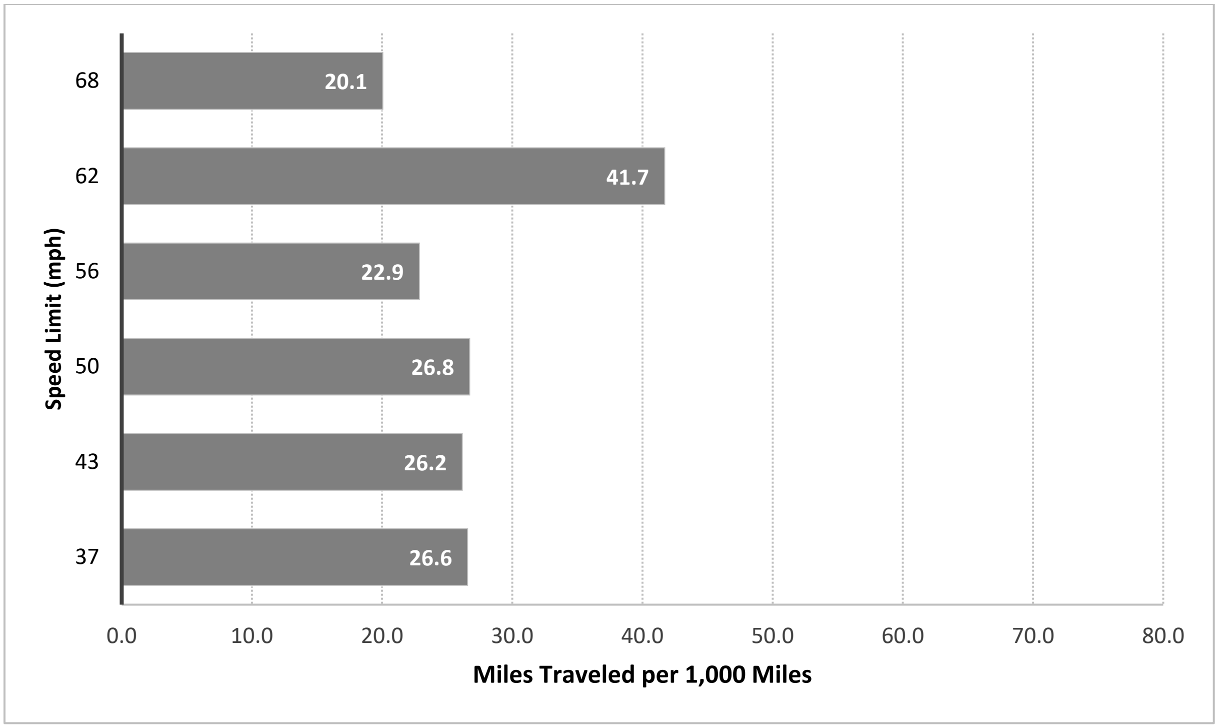

Figure E-35. Chart. Highway miles traveled in different speed limit Canadian ODDs for lane deviation type 2: 21-33 inches, outside lane (per 1,000 miles traveled).

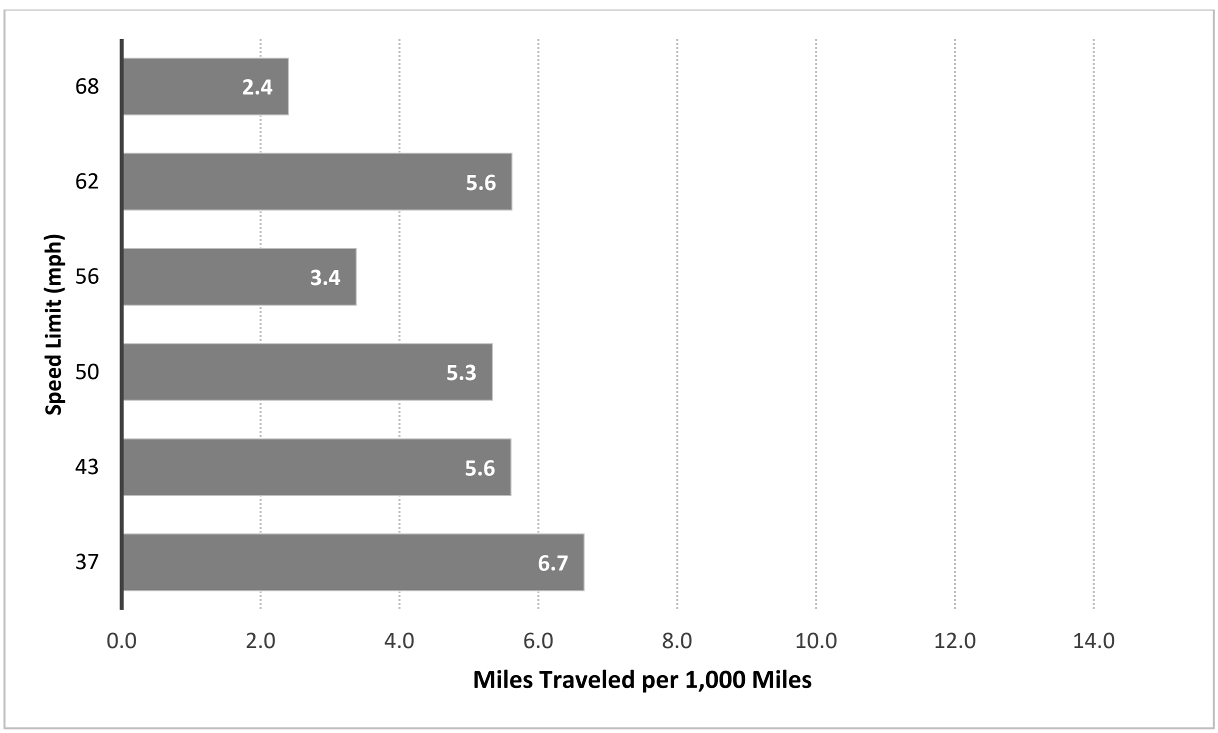

Figure E-36. Chart. Highway miles traveled in different speed limit Canadian ODDs for lane deviation type 3: 33-45 inches, outside lane (per 1,000 miles traveled).

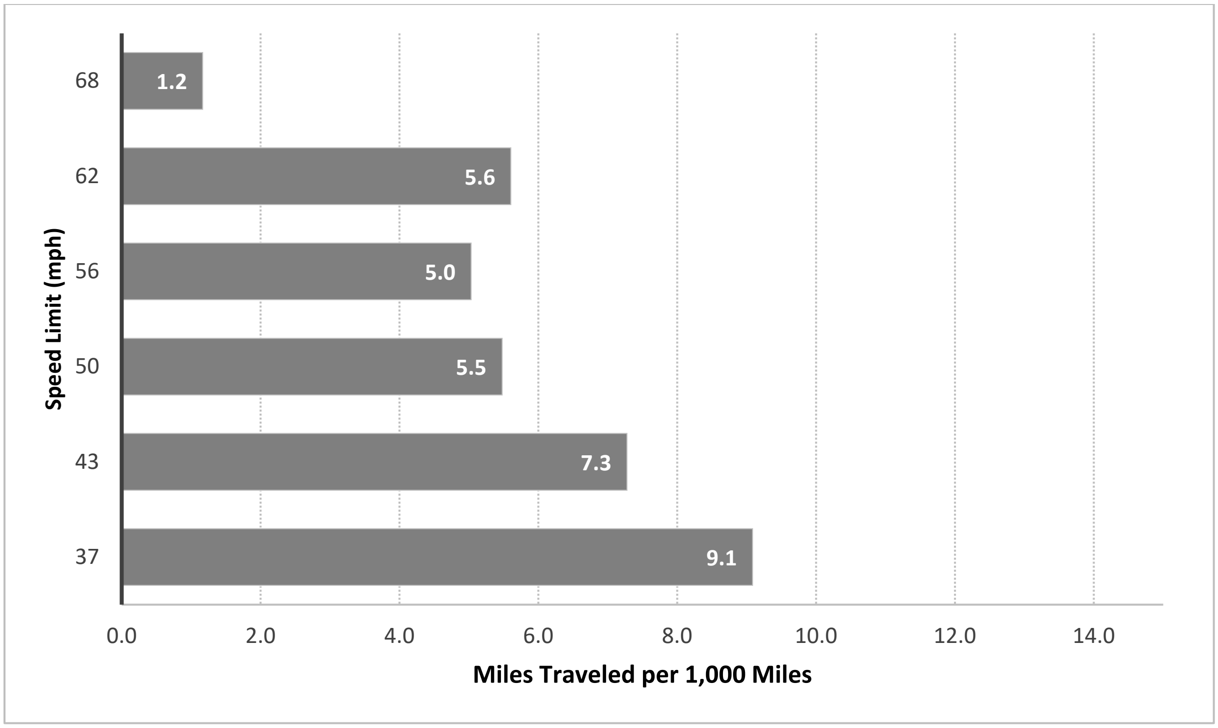

Figure E-37. Chart. Highway miles traveled in different speed limit Canadian ODDs for lane deviation type 4: greater than 45 inches, outside lane (per 1,000 miles traveled).

Lane Deviation by Number of Lanes

Table E-14 shows the distribution of lane deviation types observed for various numbers of lanes. As anticipated, the majority of the miles traveled on all highways were type 1, in which the truck was inside the lane markings. Figures D-39 through D-42 compare miles traveled for every 1,000 miles traveled on roads with different numbers of lanes and lane deviation categories of type 1, type 2, type 3, and type 4, respectively.

Table E-14. Distribution of vehicle miles per 1,000 miles exposure for each type of lane deviation compared by the available number of lanes in Canada.

Number of Lanes Canada ODD	Type 1 (0-21 inches, inside lane)	Type 2 (21-33 inches, outside lane)	Type 3 (33-45 inches, outside lane)	Type 4 (greater than 45 inches, outside lane)
1	942.1	**44.3**	**6.4**	**7.1**
2	**975.2**	20.7	2.5	1.6
3	972.4	20.1	3.5	3.9
4	971.7	19.9	3.8	4.5

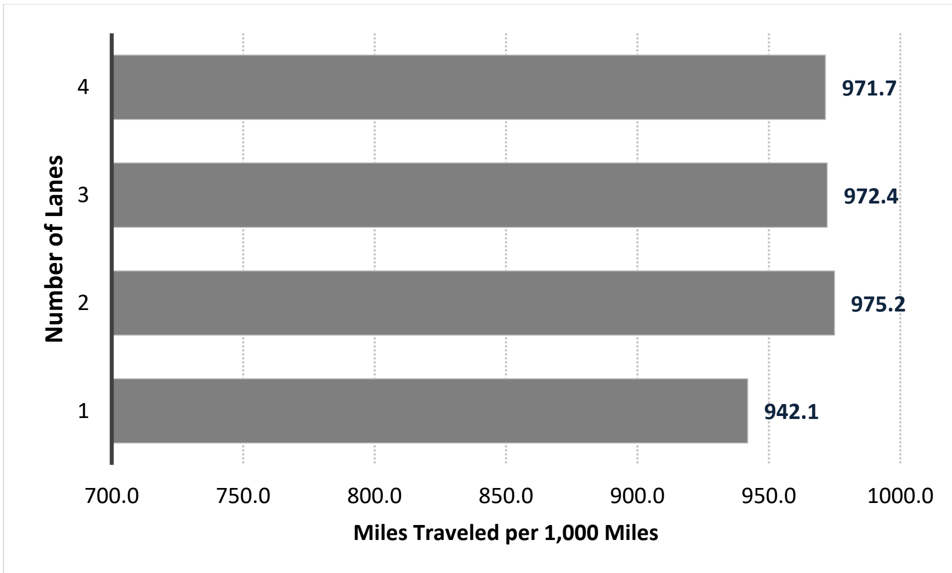

Figure E-38. Chart. Highway miles traveled by number of lanes by Canada for lane deviation type 1: 0-21 inches, inside lane (per 1,000 miles traveled).

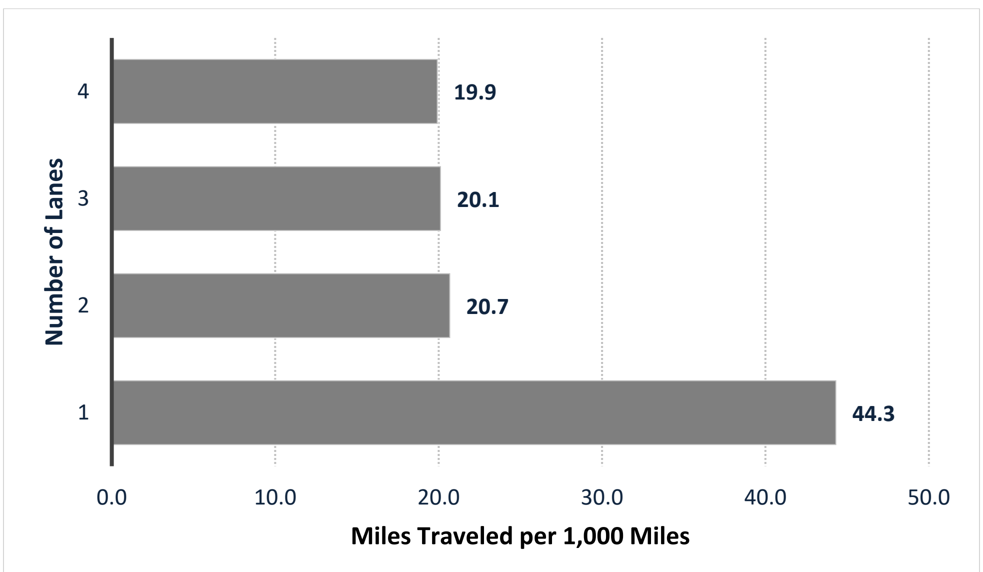

Figure E-39. Chart. Highway miles traveled by number of lanes by Canada for lane deviation type 2: 21-33 inches, outside lane (per 1,000 miles traveled).

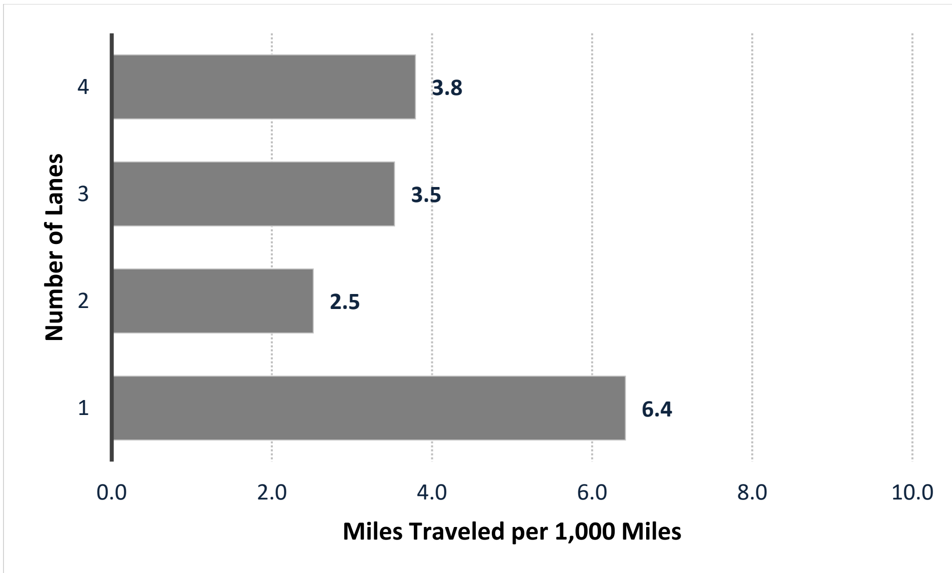

Figure E-40. Chart. Highway miles traveled by number of lanes by Canada for lane deviation type 3: 33-45 inches, outside lane (per 1,000 miles traveled).

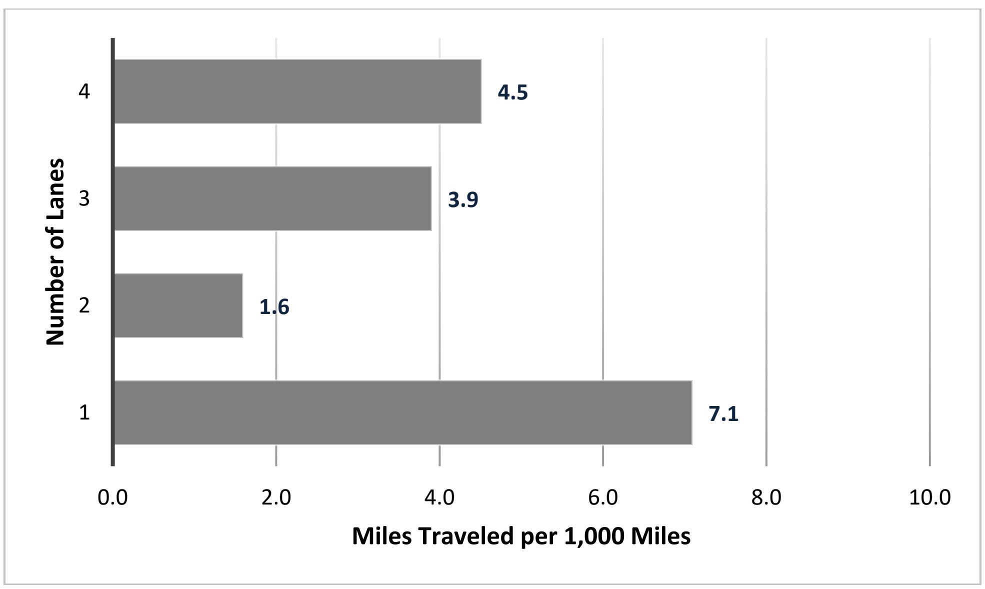

Figure E-41. Chart. Highway miles traveled by number of lanes by Canada for lane deviation type 4: greater than 45 inches, outside lane (per 1,000 miles traveled).

Lane Stability

Lane stability is defined by three features calculated from the lane offset signal in each link ID.

- Type 1: mean absolute value of lane deviation computed for each link ID. (Note that while using absolute value, this feature does not consider whether the deviation is on the left side or right side.)
- Type 2: standard deviation of lane deviation computed for each link ID.

- Type 3: maximum lane deviation computed for each link ID.

For each type, the statistics were computed for specific ODDs, as defined by the interstate name, speed limit, and number of lanes. Each table shown in the following sections reports mean value, standard deviation (std), 25th quartile (Q1), 50th quartile (Q2), and 75th quartile (Q3) of a specific feature computed for the whole exposure available in the specified ODD. See Section 4.4.6 for a more complete explanation of lane stability calculations.

Lane stability by speed limit

Tables E-15, E-16, and E-17 show all the statistics comparing the roads with various speed limits for type 1, type 2, and type 3 lane stability features. Figures E-42 through E-44 show box plots of the three types, displaying the distributions of the naturalistic data.

Table E-15. Lane stability type 1 statistics by six speed limit Canadian ODDs.

Speed Limit Canada ODD (mph)	Mean	Std	Q1	Q2	Q3
37	9.8	8.4	4.6	7.5	12.1
43	9.8	8.4	4.6	7.5	12.3
50	9.2	7.3	4.5	7.3	11.7
56	9.3	8.5	4.7	7.4	11.6
62	9.3	6.9	4.9	7.6	11.6
68	8.0	5.6	4.6	6.8	9.9

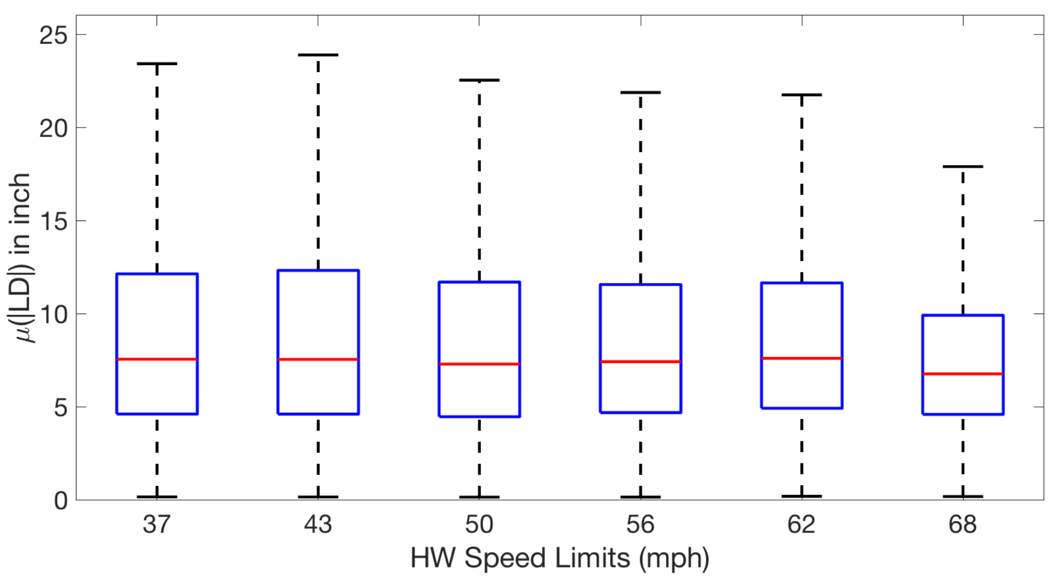

Figure E-42. Chart. Lane stability type 1 by speed limit Canadian ODDs.

Table E-16. Lane stability type 2 statistics by six speed limit Canadian ODDs.

Speed Limit ODD Canada (mph)	Mean	Std	Q1	Q2	Q3
37	5.8	5.7	2.3	4.2	7.2
43	5.5	5.5	2.3	3.9	6.6
50	5.7	5.3	2.4	4.2	7.1
56	5.3	5.1	2.0	4.0	6.7
62	5.7	4.5	2.8	4.8	7.3
68	5.5	3.8	2.9	4.9	7.2

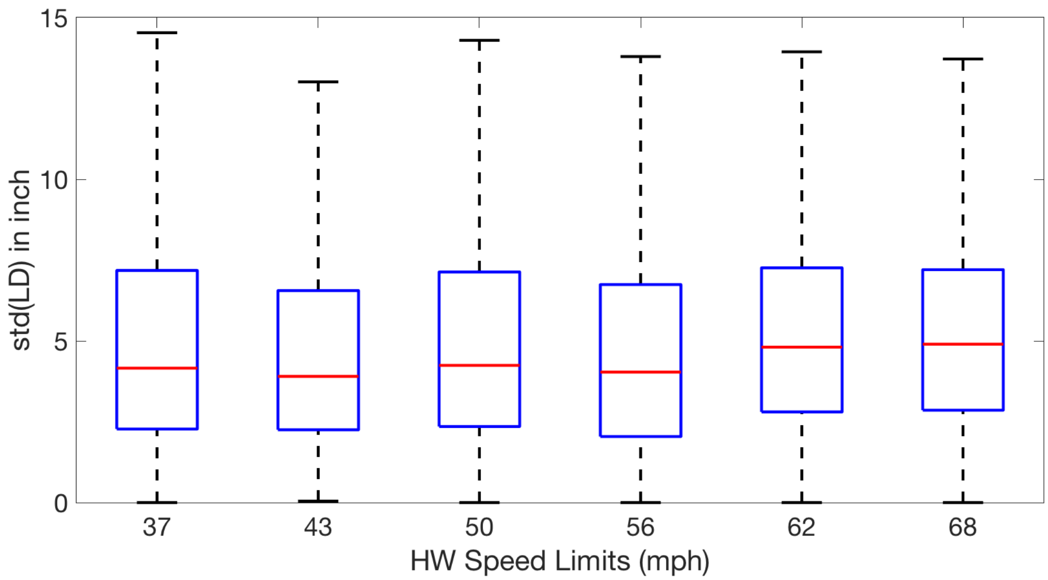

Figure E-43. Chart. Lane stability type 2 by speed limit Canadian ODDs.

Table E-17. Lane stability type 3 statistics by six speed limit Canadian ODDs.

Speed Limit ODD Canada (mph)	Mean	Std	Q1	Q2	Q3
37	22.7	18.3	10.2	16.7	27.8
43	21.1	16.6	10.1	16.0	25.4
50	20.9	16.2	10.1	16.0	25.5
56	19.9	16.4	9.8	15.5	23.5
62	21.7	15.0	11.7	18.0	26.4
68	19.3	12.8	11.2	16.7	23.5

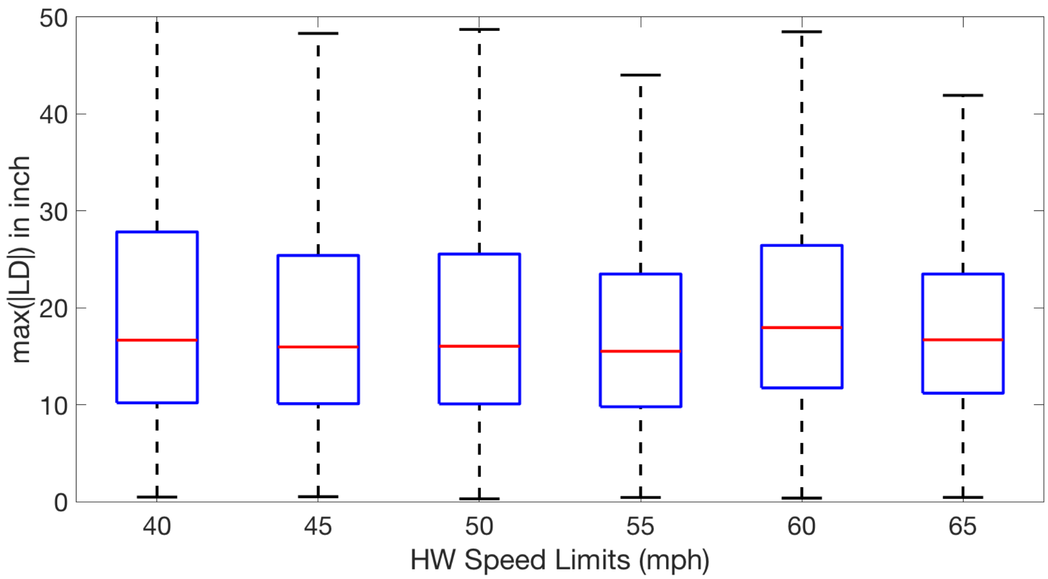

Figure E-44. Chart. Lane stability type 3 by speed limit Canadian ODDs.

Lane Stability by Number of Lanes

Tables E-18 through E-20 show all the statistics for roads with various numbers of lanes for type 1, type 2, and type 3 lane stability features. Figures E-45 through E-47 show box plots of the three types, displaying the distributions of the naturalistic data.

Table E-18. Lane stability type 1 statistics by four number of lane Canadian ODDs.

Number of Lanes Canada ODD	Mean	Std	Q1	Q2	Q3
1	9.4	7.1	5.0	7.6	11.7
2	8.4	6.4	4.7	7.0	10.4
3	9.2	8.8	4.1	7.0	11.6
4	8.7	8.0	3.6	6.6	11.2

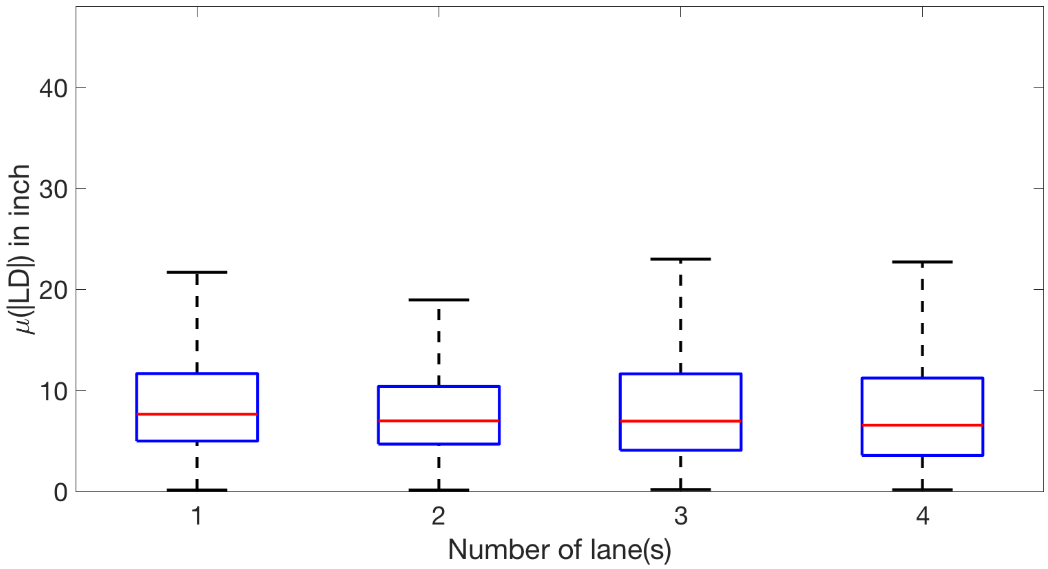

Figure E-45. Chart. Lane stability type 1 by number of highway lane Canadian ODDs.

Table E-19. Lane stability type 2 statistics by four number of lane Canadian ODDs.

Number of Lanes Canada ODD	Mean	Std	Q1	Q2	Q3
1	5.8	4.8	2.6	4.8	7.5
2	5.7	4.2	2.9	4.9	7.3
3	4.5	5.0	1.6	3.0	5.4
4	3.4	4.3	1.2	2.1	3.9

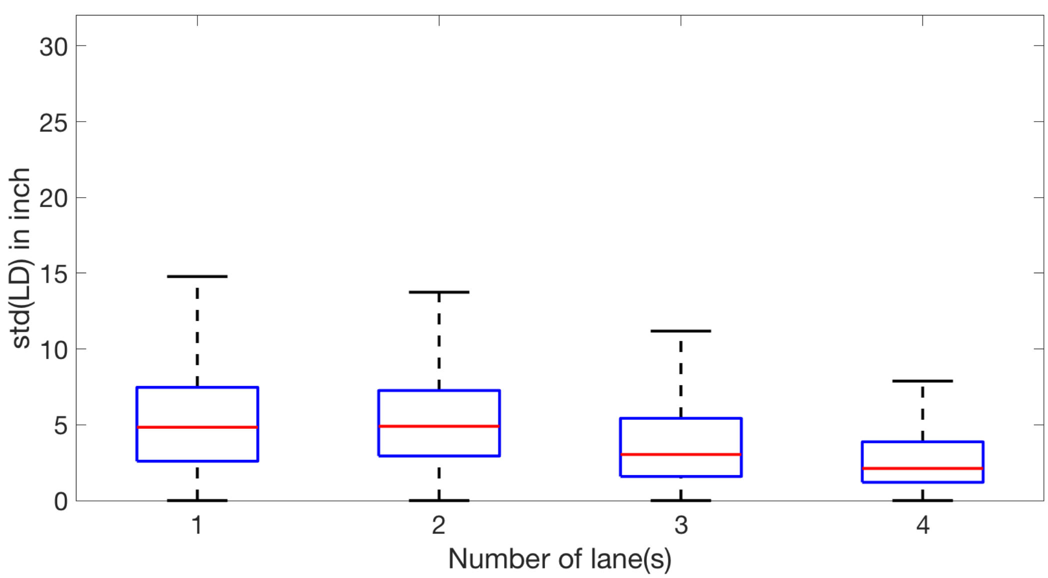

Figure E-46. Chart. Lane stability type 2 by number of highway lane Canadian ODDs.

Table E-20. Lane stability type 3 statistics by four number of lane Canadian ODDs.

Number of Lanes Canada ODD	Mean	Std	Q1	Q2	Q3
1	21.6	15.7	11.3	17.6	26.4
2	20.2	14.1	11.4	17.0	24.2
3	17.9	15.6	8.4	13.6	21.5
4	15.1	13.3	7.1	11.3	18.0

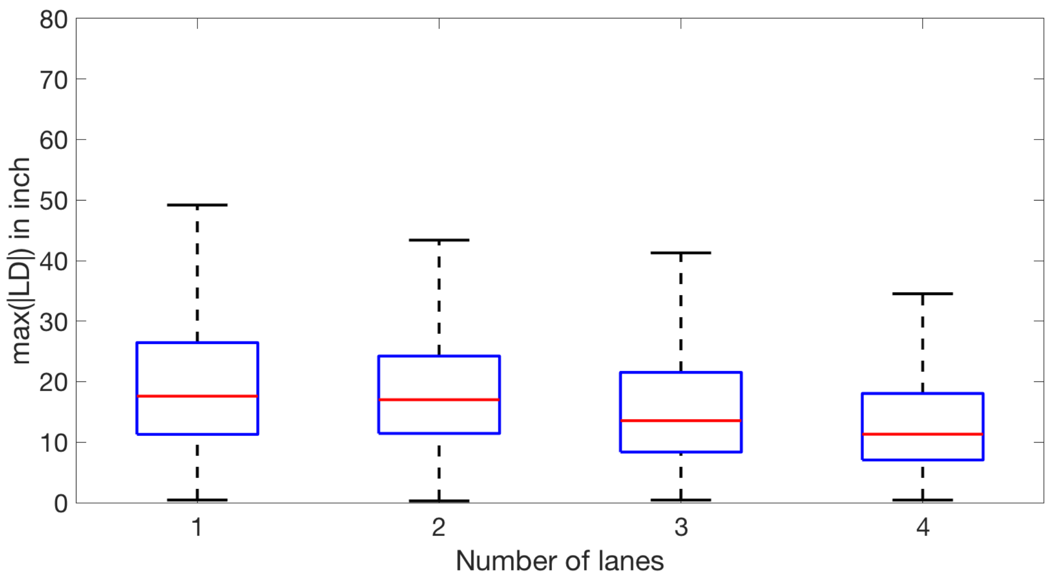

Figure E-47. Chart. Lane stability type 3 by number of highway lane Canadian ODDs.

APPENDIX F. BAR CHARTS FOR U.S. LEADING BASELINES

SPEED BEHAVIOR

Speed Behavior by Highway ODD

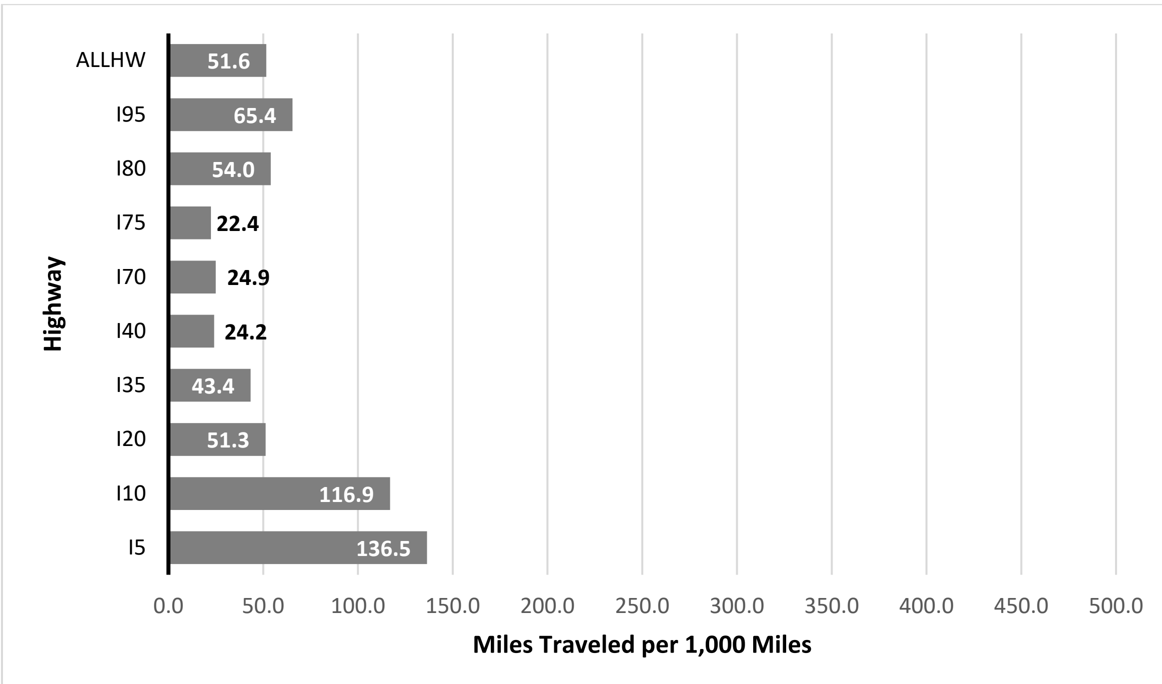

Figure 11. Chart. Highway miles traveled at speed behavior type 1: 15 to 10 mph below limit (per 1,000 miles traveled) for 10 highway ODDs.

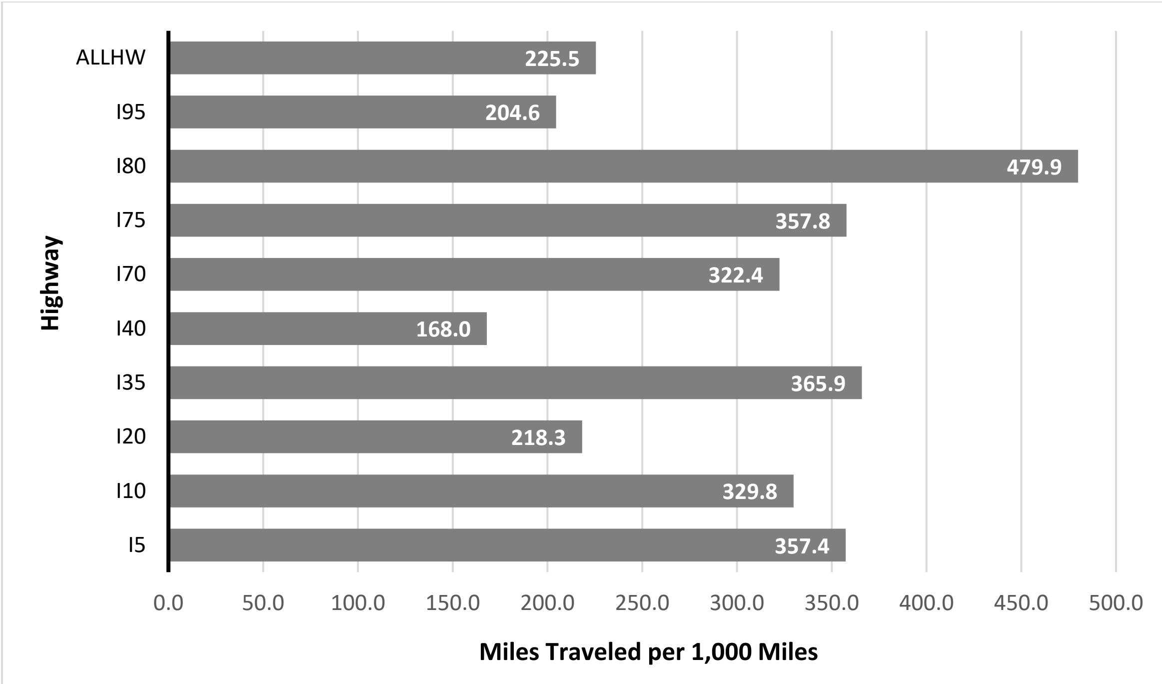

Figure 12. Chart. Highway miles traveled at speed behavior type 2: 10 to 5 mph below limit (per 1,000 miles traveled) for 10 highway ODDs.

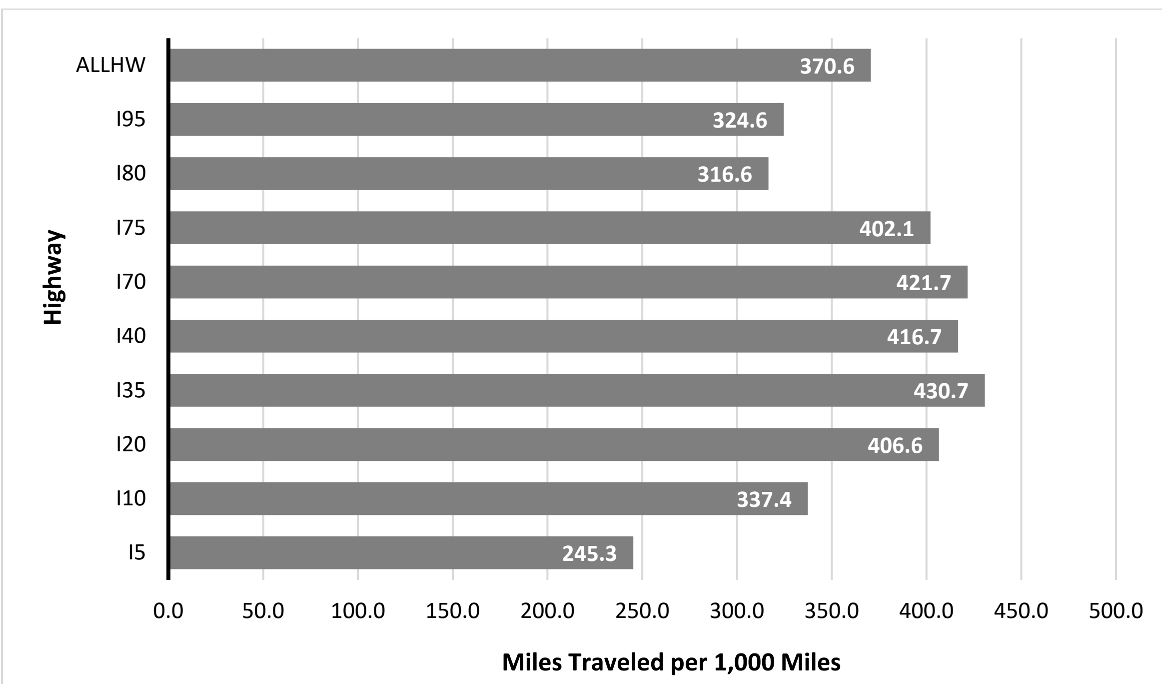

Figure 13. Chart. Highway miles traveled at speed behavior type 3: 5 mph below limit to limit (per 1,000 miles traveled) for 10 highway ODDs.

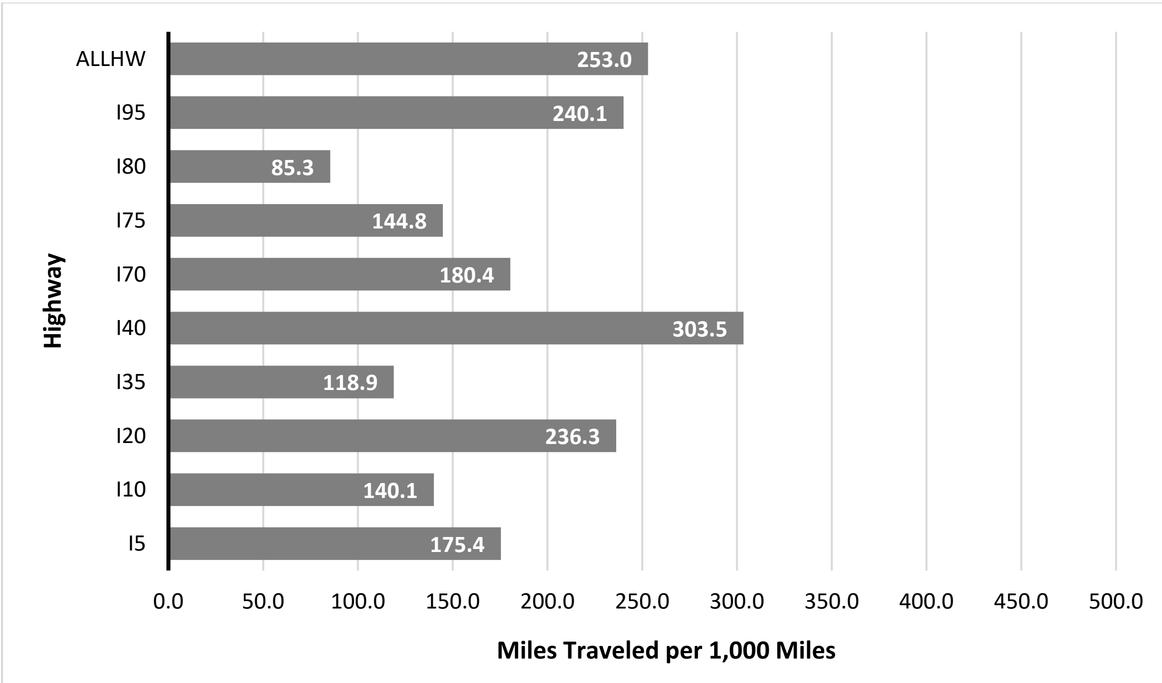

Figure 14. Chart. Highway miles traveled at speed behavior type 4: limit to 5 mph above limit (per 1,000 miles traveled) for 10 highway ODDs.

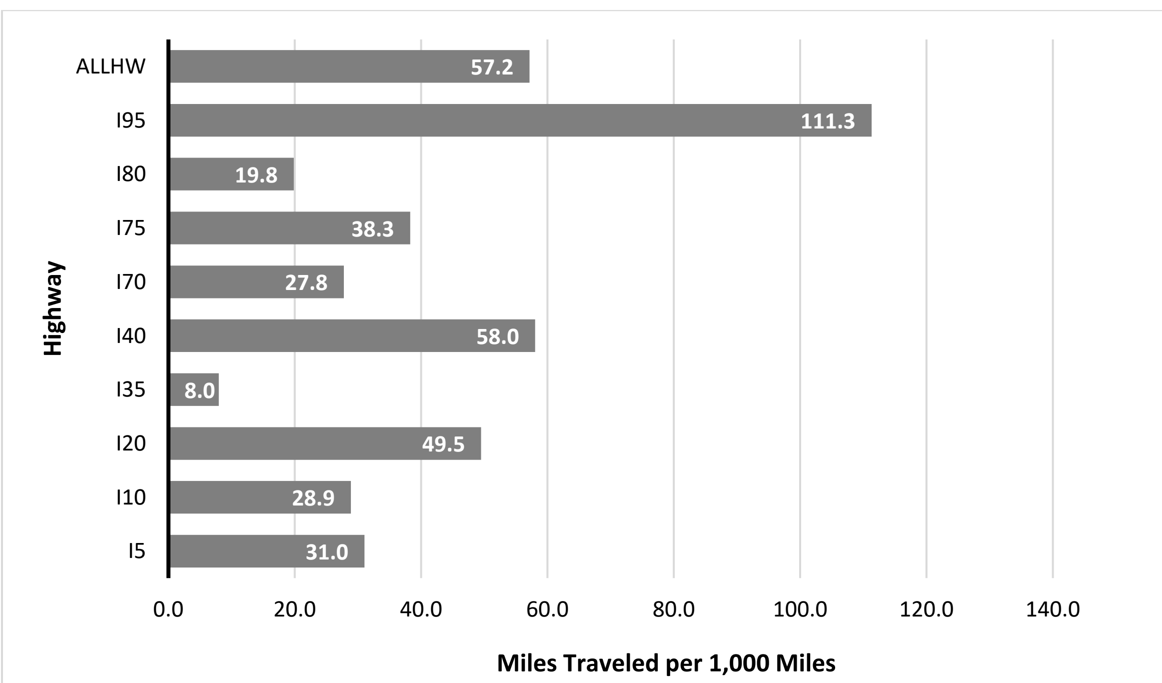

Figure 15. Chart. Highway miles traveled at speed behavior type 5: 5 to 10 mph above limit (per 1,000 miles traveled) for 10 highway ODDs.

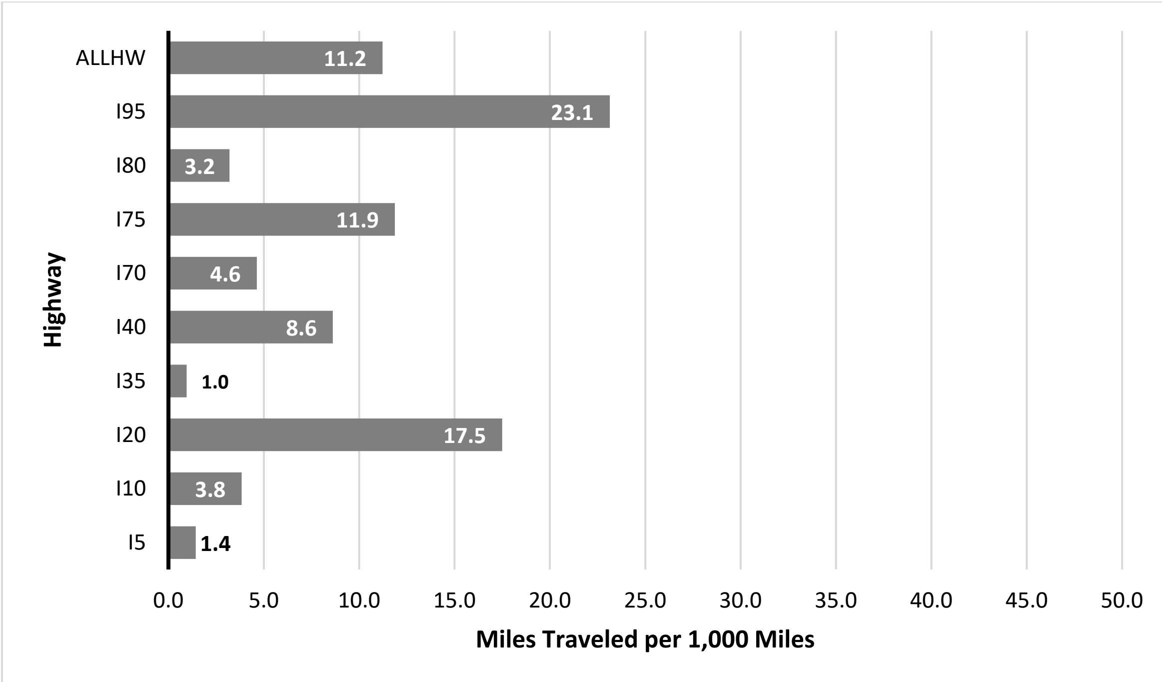

Figure 16. Chart. Highway miles traveled at speed behavior type 6: 10 to 15 mph above limit (per 1,000 miles traveled) for 10 highway ODDs.

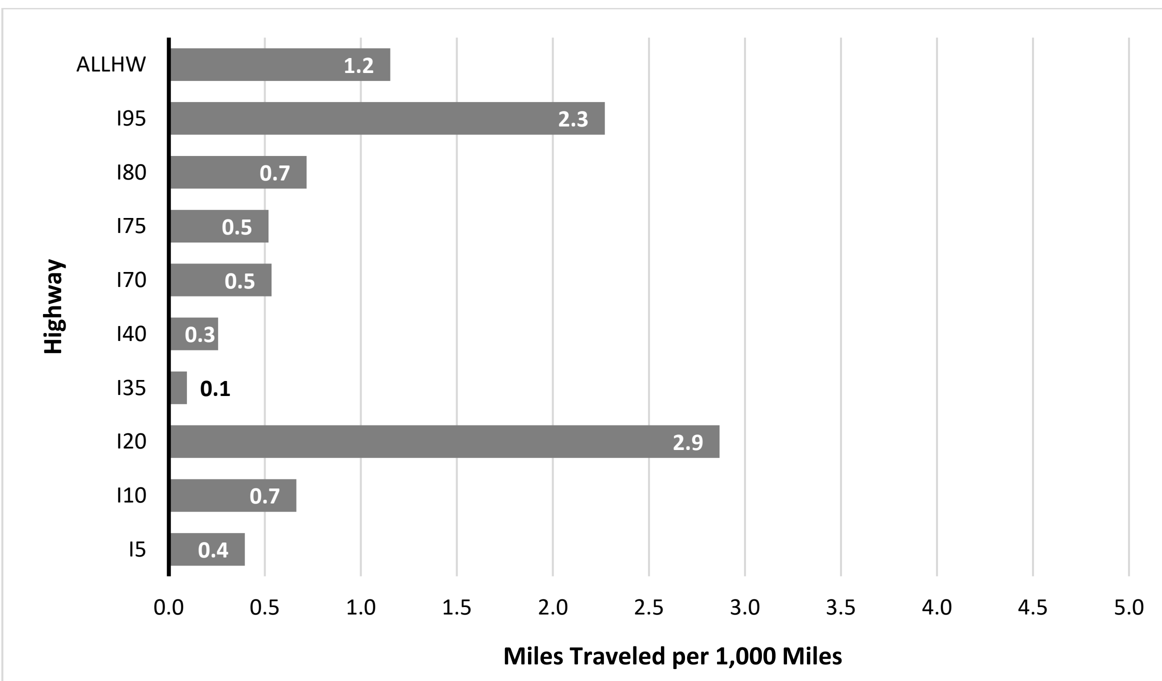

Figure 17. Chart. Highway miles traveled at speed behavior type 7: 15 to 20 mph above limit (per 1,000 miles traveled) for 10 highway ODDs.

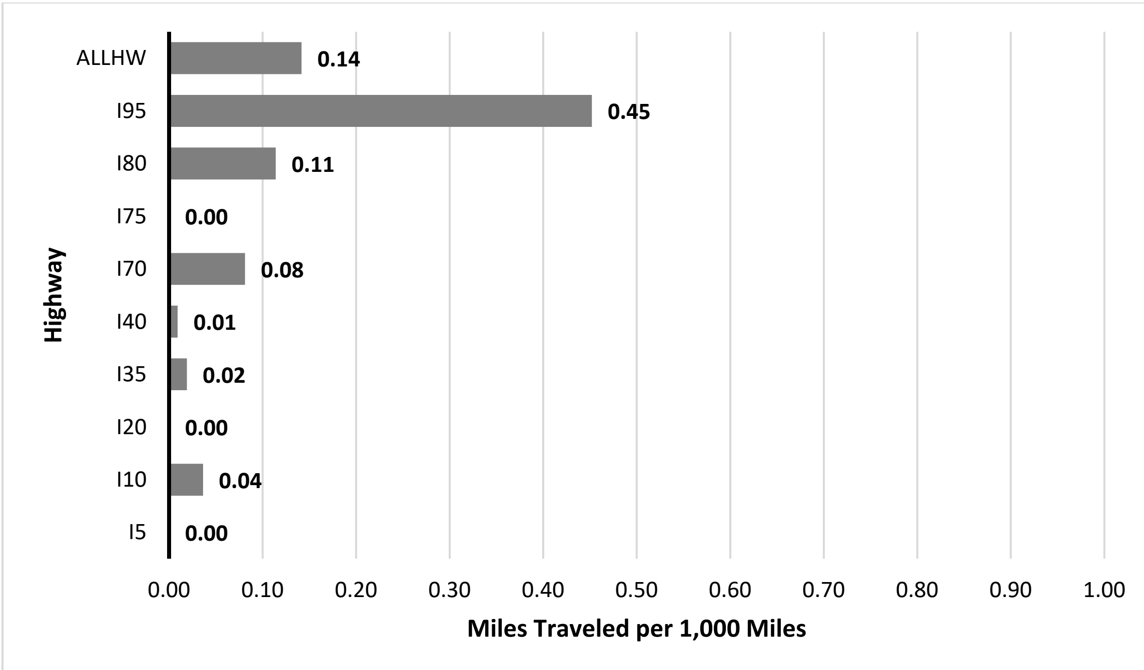

Figure 18. Chart. Highway miles traveled at speed behavior type 8: 20 mph or more above limit (per 1,000 miles traveled) for 10 highway ODDs.

Speed Behavior by Speed Limit ODD

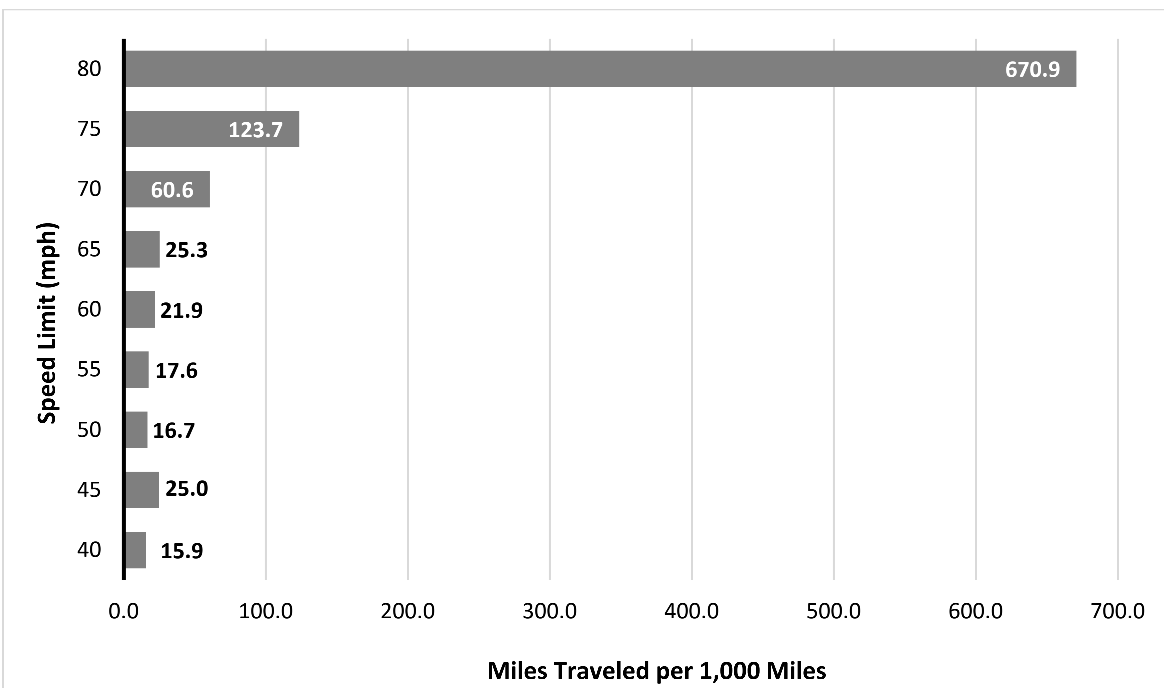

Figure 19. Chart. Highway miles (per 1,000 miles traveled) in 9 speed limit ODDs for speed behavior type 1: 15 to 10 mph below limit.

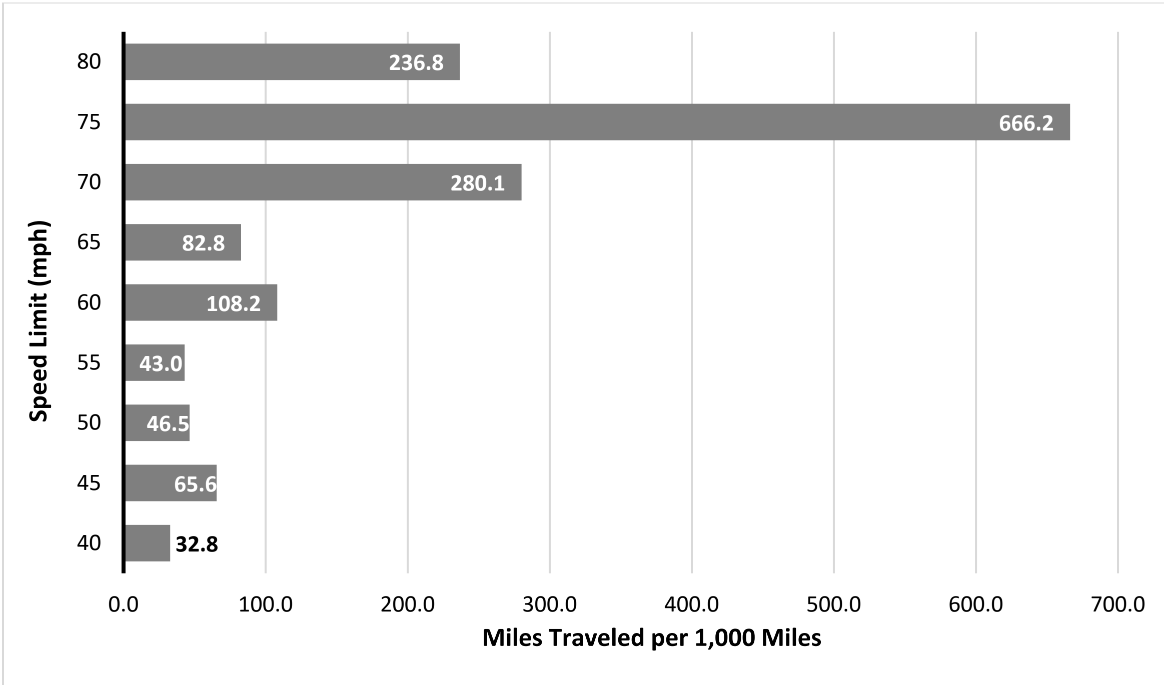

Figure 20. Chart. Highway miles (per 1,000 miles traveled) in 9 speed limit ODDs for speed behavior type 2: 10 to 5 mph below limit.

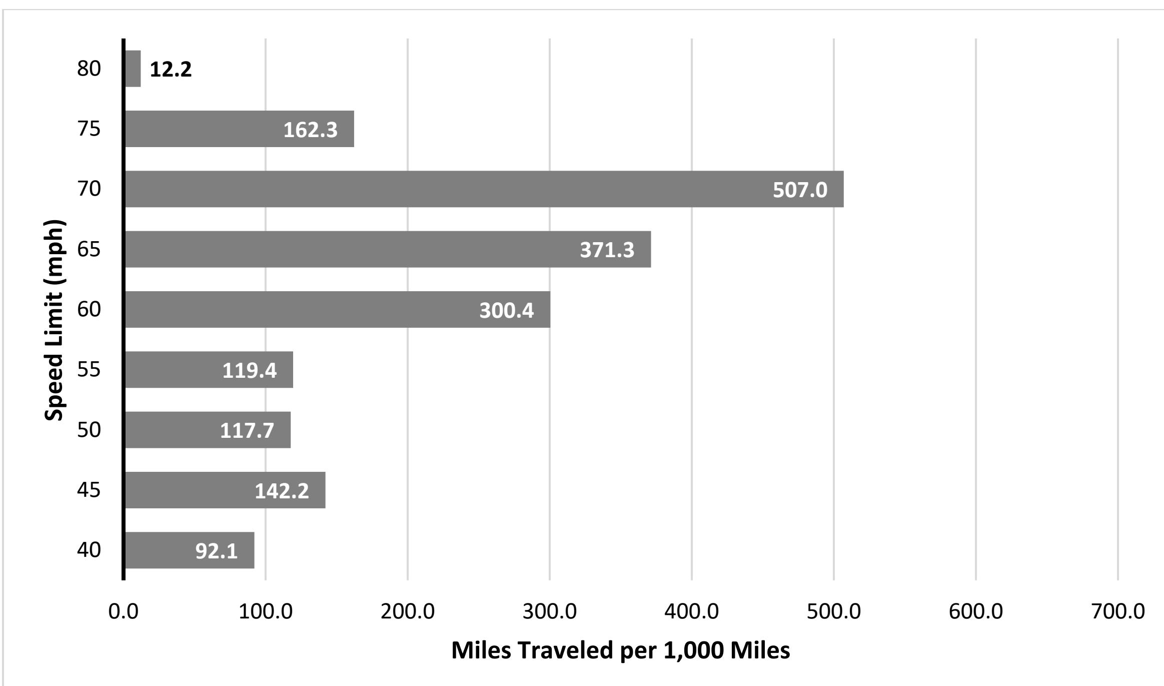

Figure 21. Chart. Highway miles (per 1,000 miles traveled) in 9 speed limit ODDs for speed behavior type 3: 5 to 0 mph below limit.

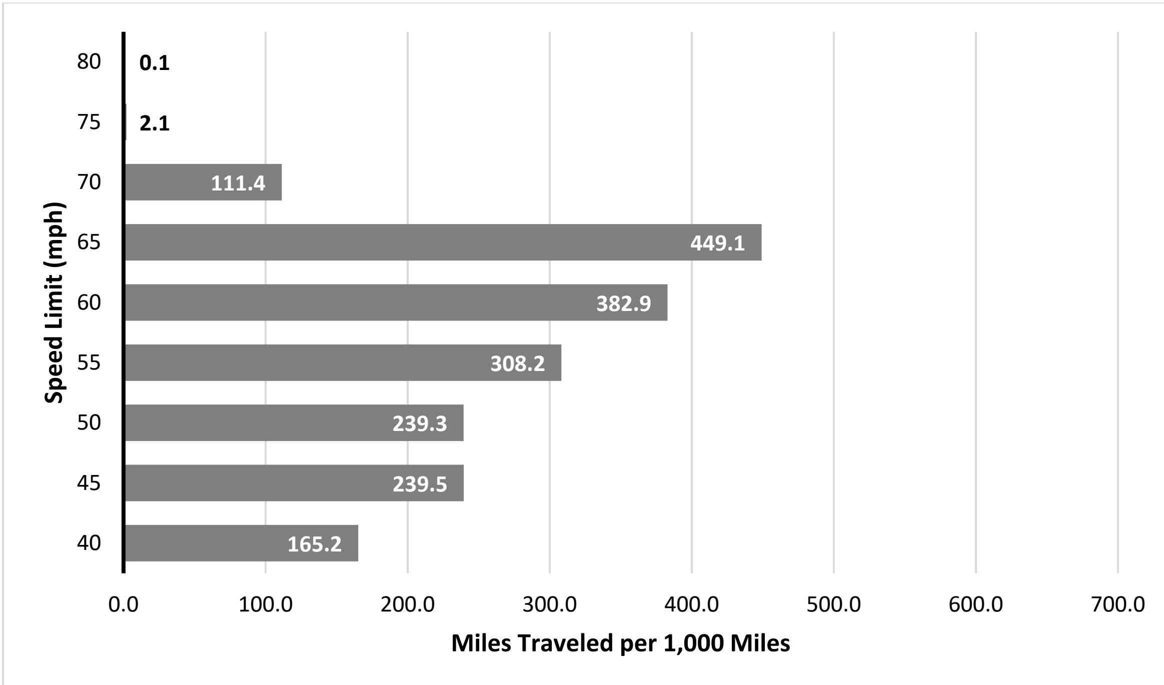

Figure 22. Chart. Highway miles (per 1,000 miles traveled) in nine speed limit ODDs for speed behavior type 4: 0 to 5 mph above limit.

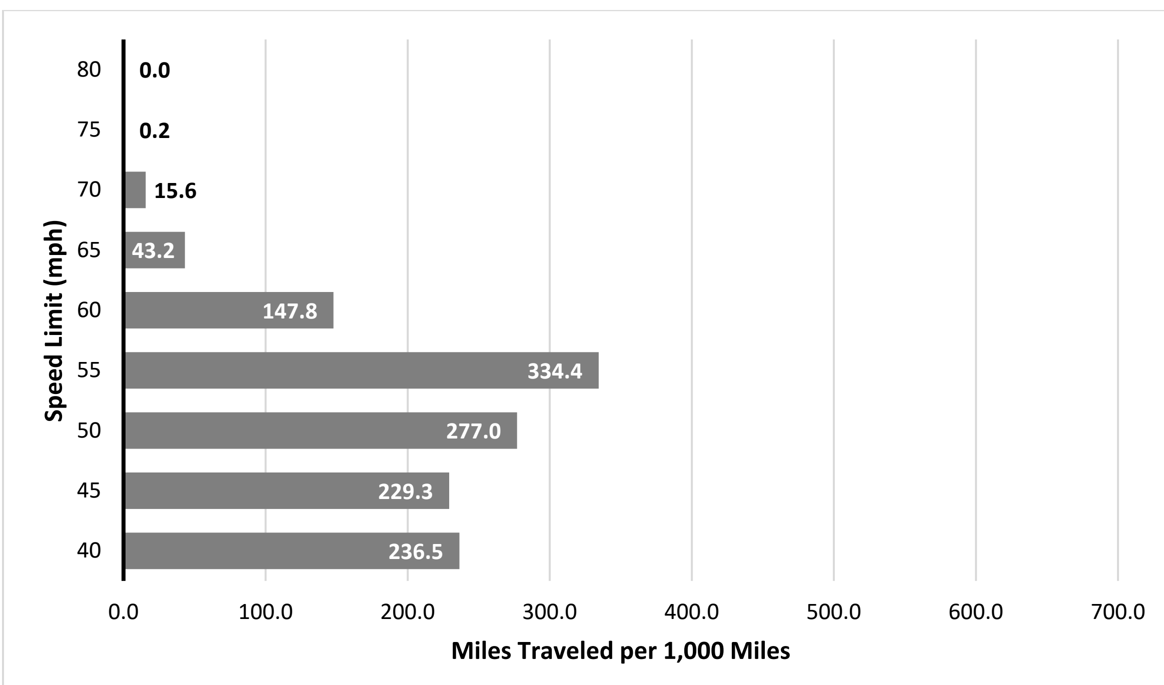

Figure 23. Chart. Highway miles (per 1,000 miles traveled) in nine speed limit ODDs for speed behavior type 5: 5 to 10 mph above limit.

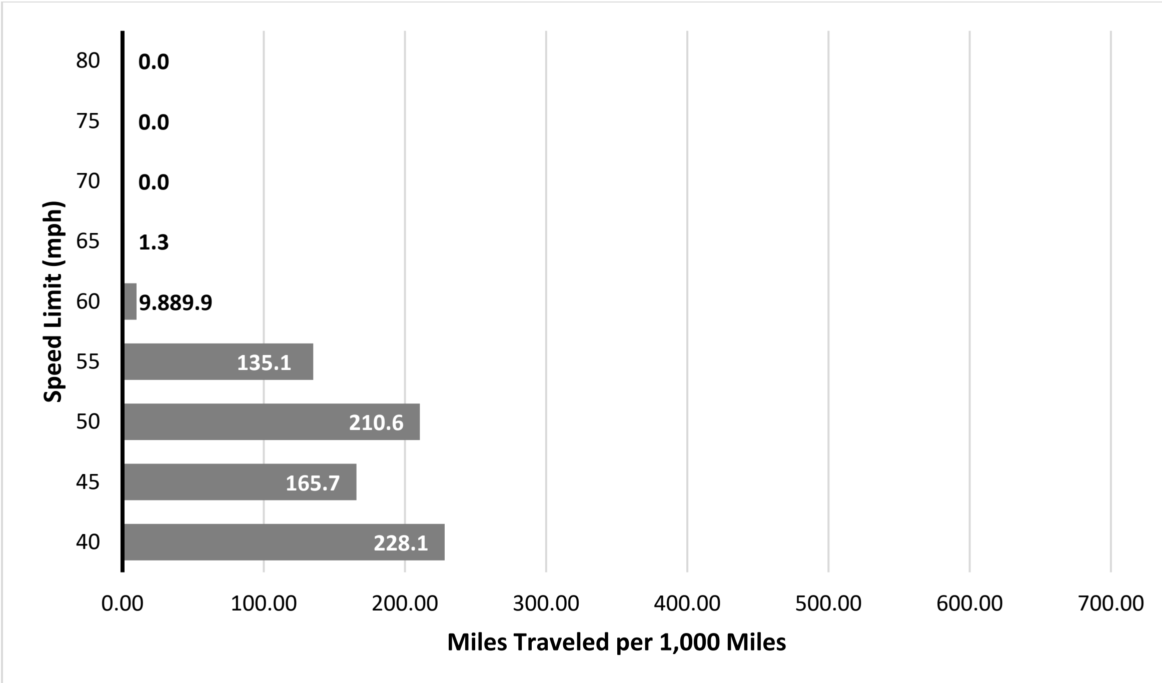

Figure 24. Chart. Highway miles (per 1,000 miles traveled) in nine speed limit ODDs for speed behavior type 6: 10 to 15 mph above limit.

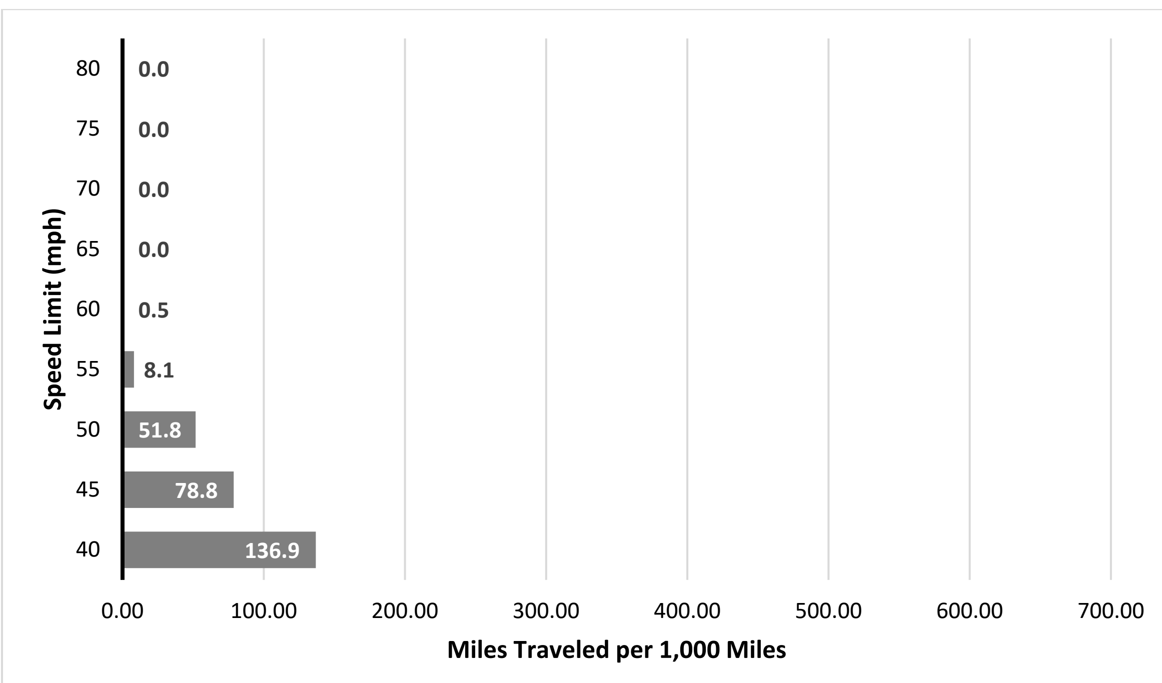

Figure 25. Chart. Highway miles (per 1,000 miles traveled) in nine speed limit ODDs for speed behavior type 7: 15 to 20 mph above limit.

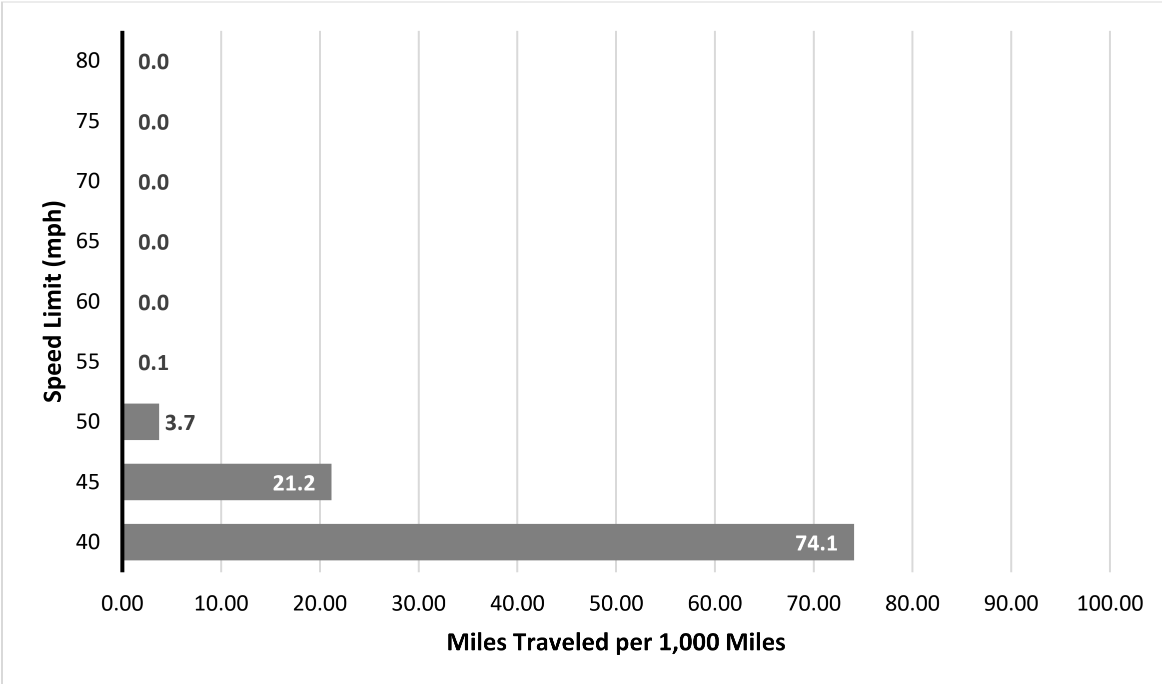

Figure 26. Chart. Highway miles (per 1,000 miles traveled) in nine speed limit ODDs for speed behavior type 8: 20 mph or more above limit.

Speed Behavior by Number of Lanes

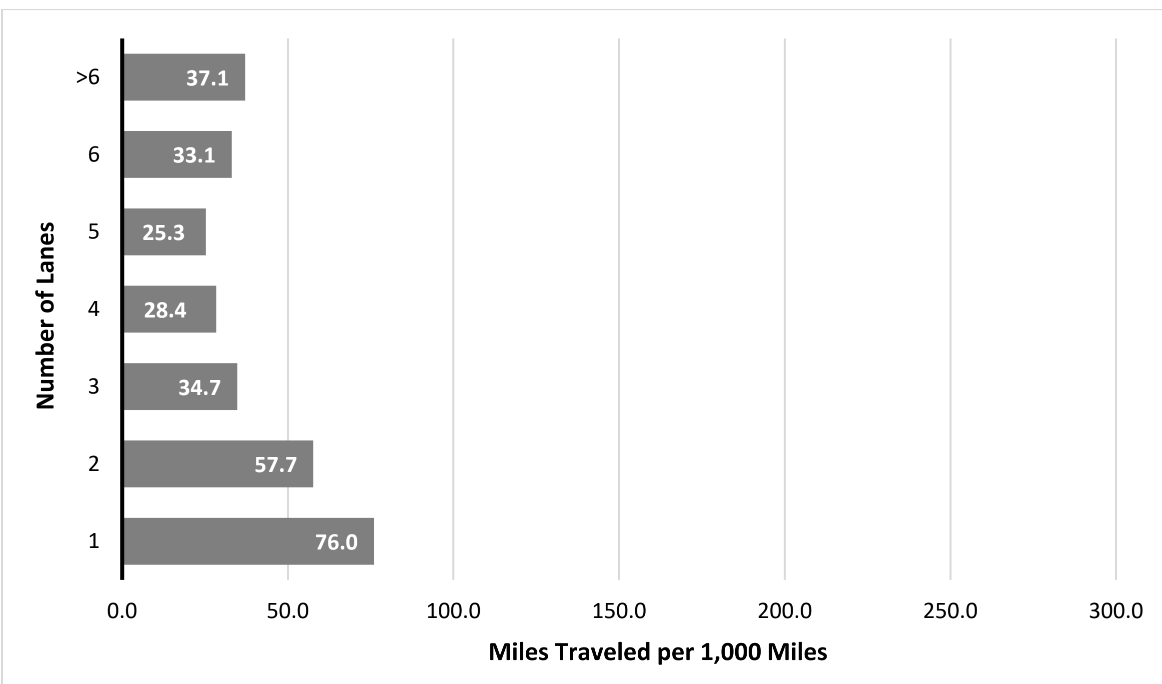

Figure 27. Chart. Highway miles (per 1,000 miles traveled) by number of lanes for speed behavior type 1: 15 to 10 mph below limit.

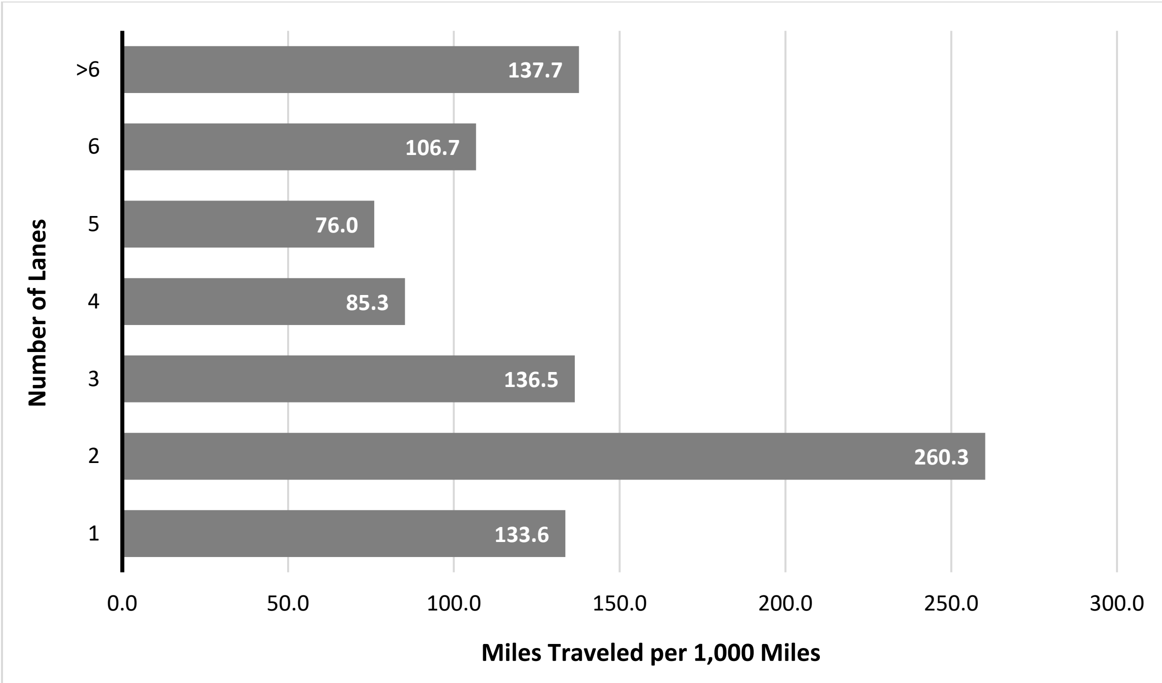

Figure 28. Chart. Highway miles (per 1,000 miles traveled) by number of lanes for speed behavior type 2: 10 to 5 mph below limit.

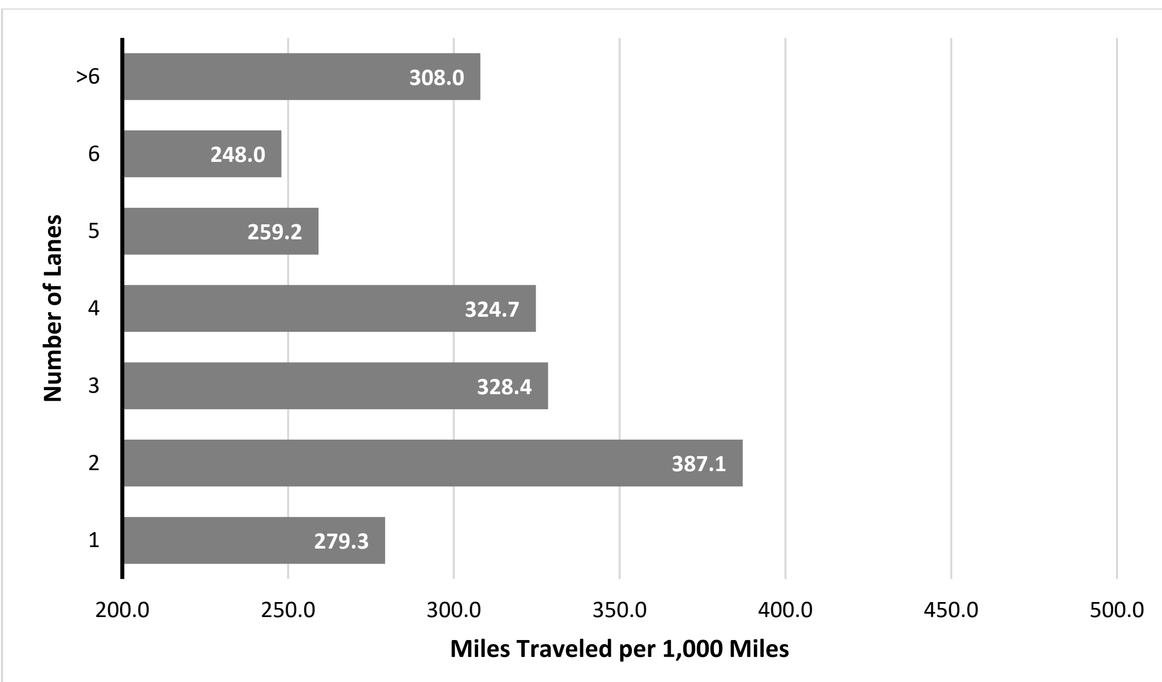

Figure 29. Chart. Highway miles (per 1,000 miles traveled) by number of lanes for speed behavior type 3: 5 mph below limit to limit.

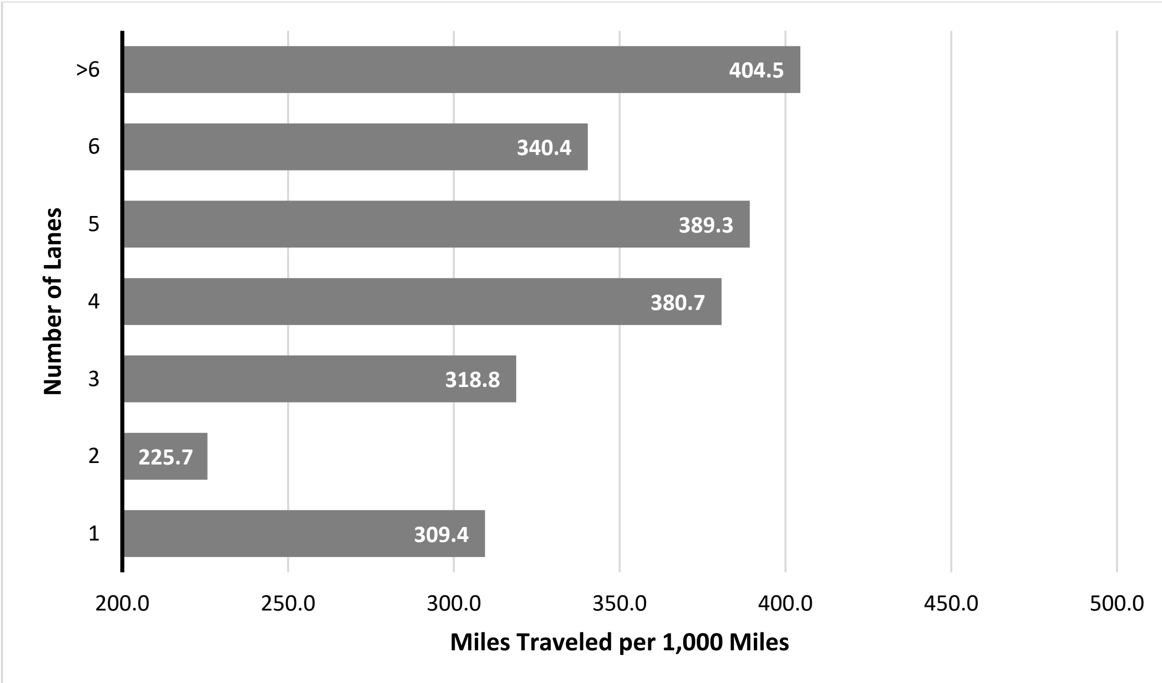

Figure 30. Chart. Highway miles (per 1,000 miles traveled) by number of lanes for speed behavior type 4: limit to 5 mph above limit.

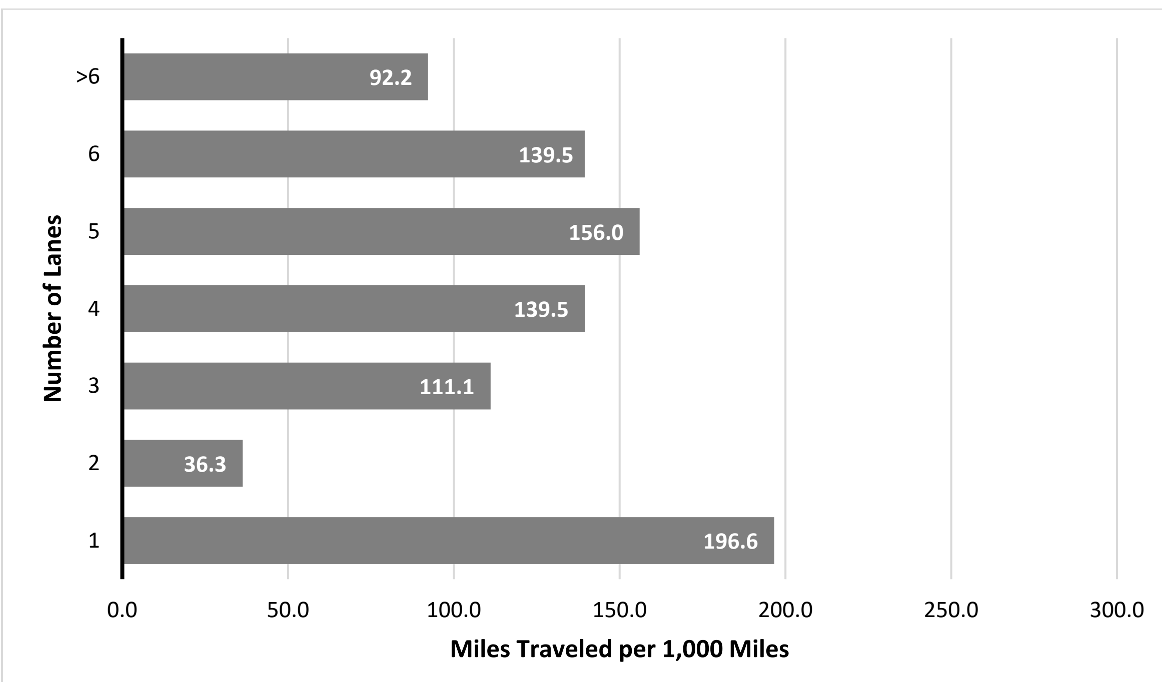

Figure 31. Chart. Highway miles (per 1,000 miles traveled) by number of lanes for speed behavior type 5: 5 to 10 mph above limit.

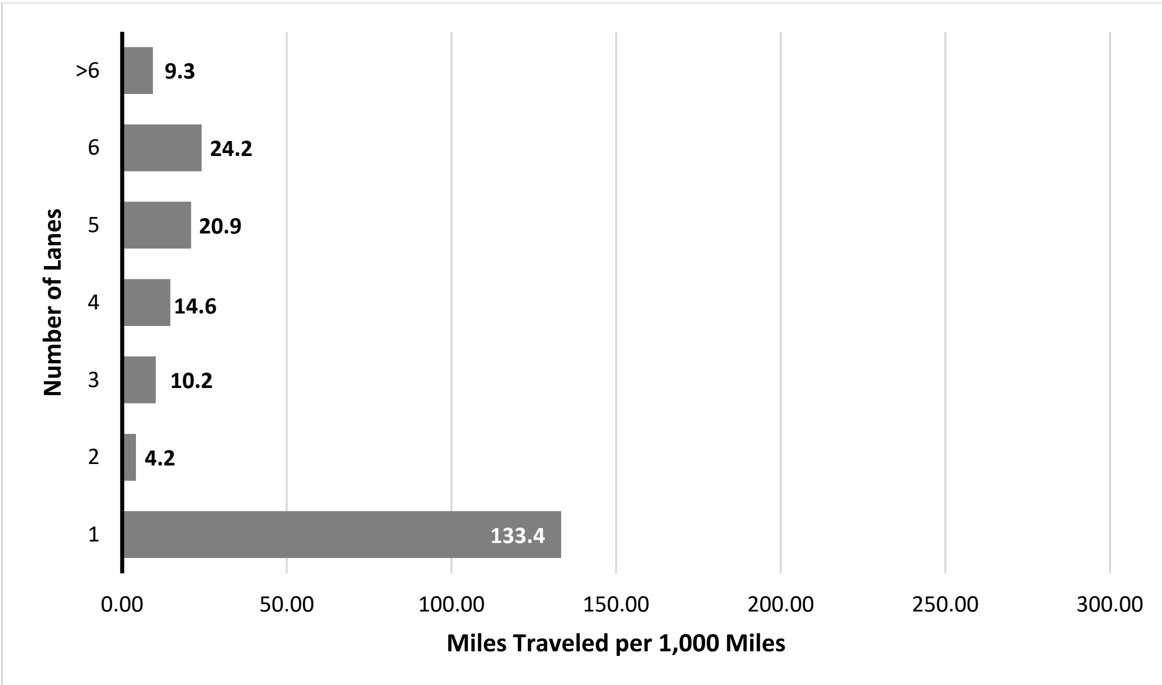

Figure 32. Chart. Highway miles (per 1,000 miles traveled) by number of lanes for speed behavior type 6: 10 to 15 mph above limit.

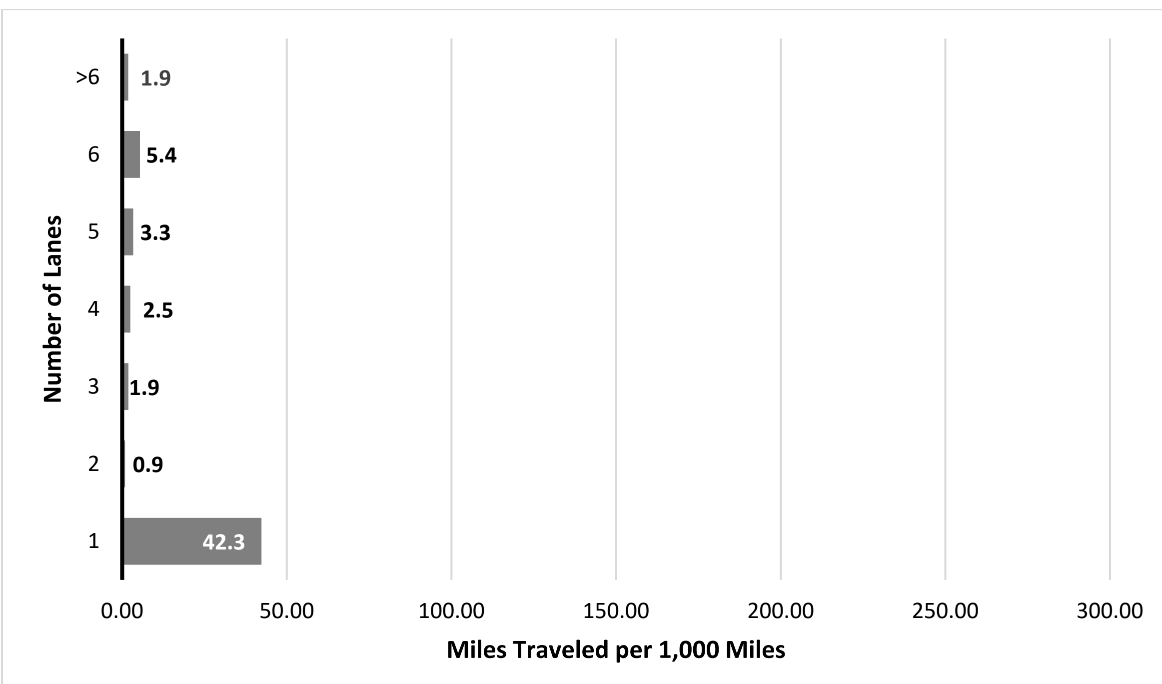

Figure 33. Chart. Highway miles (per 1,000 miles traveled) by number of lanes for speed behavior type 7: 15 to 20 mph above limit.

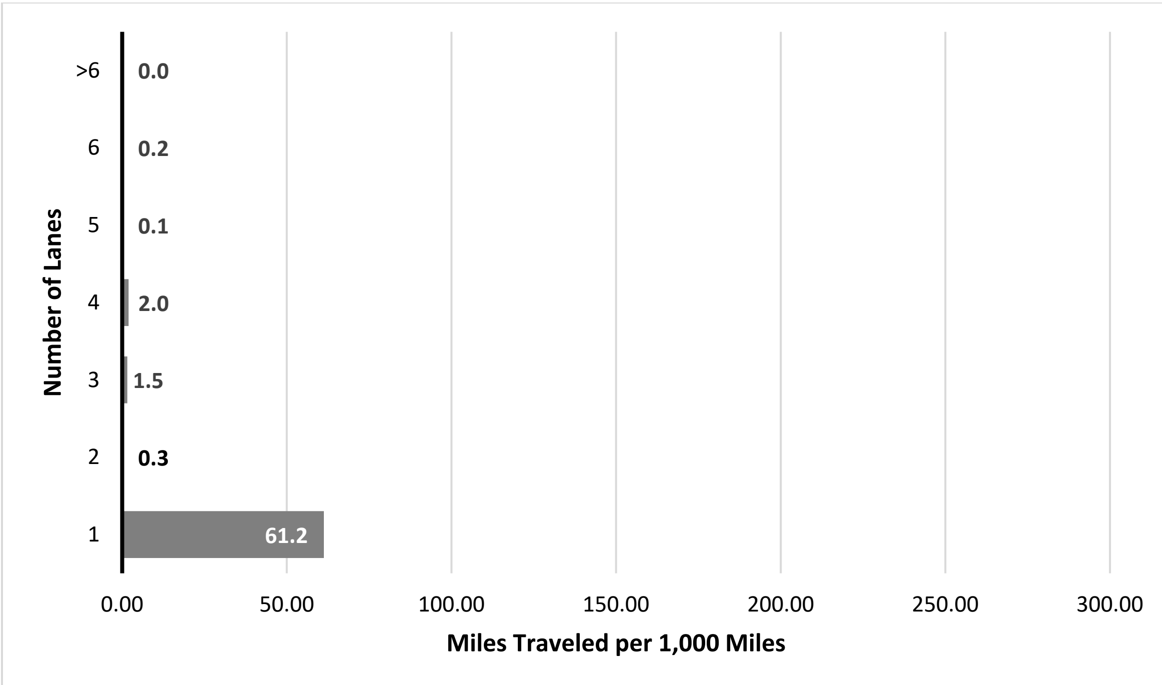

Figure 34. Chart. Highway miles (per 1,000 miles traveled) by number of lanes for speed behavior type 8: 20 mph or more above limit.

LATERAL ACCELERATION

Lateral Acceleration Behavior by Highway ODD

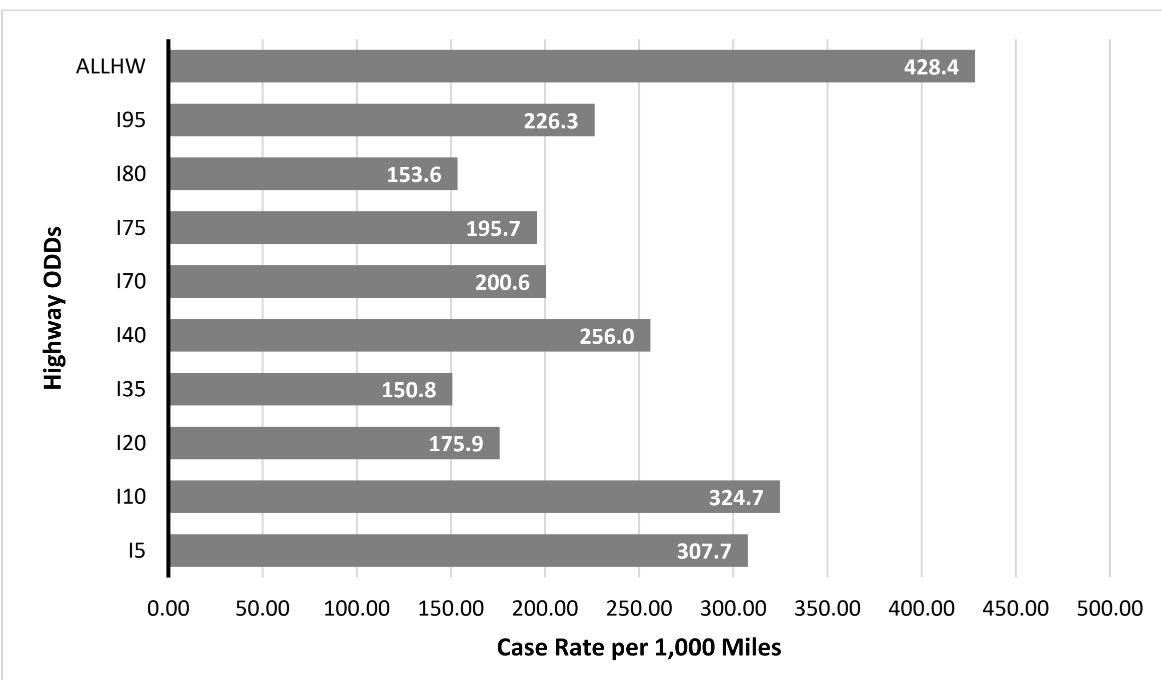

Figure 35. Chart. Case frequency in 10 highway ODDs for lateral acceleration type 1: 0.1 g to 0.2 g (per 1,000 miles traveled).

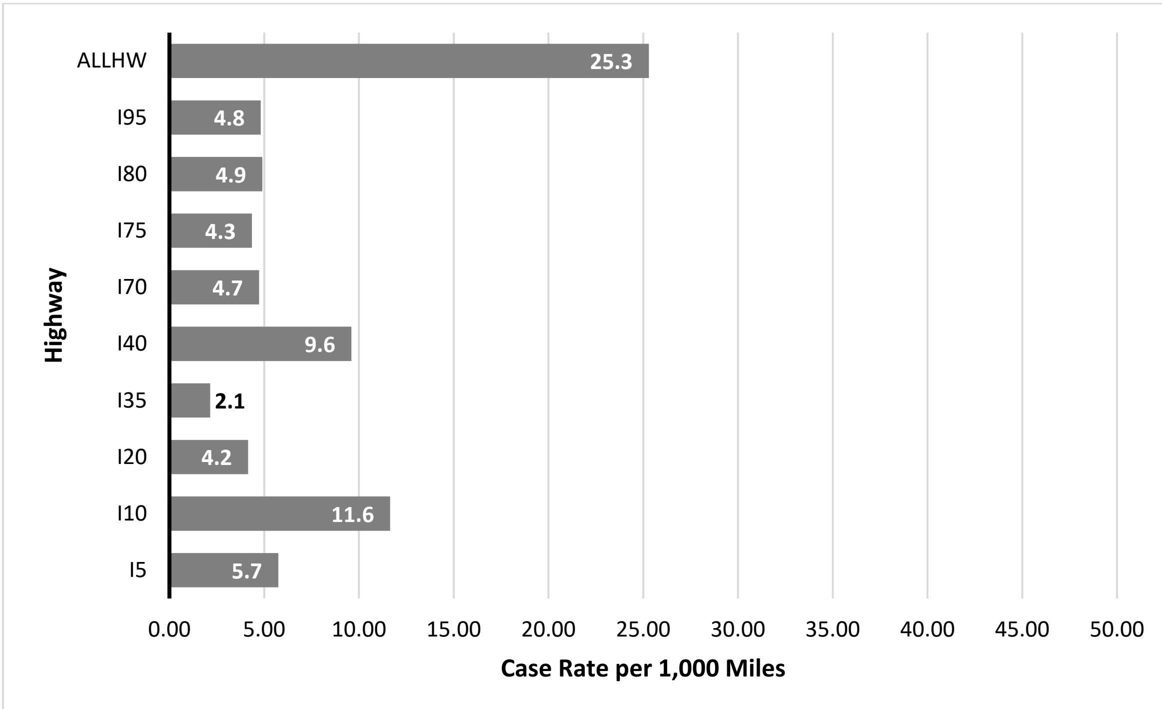

Figure 36. Chart. Case frequency in 10 highway ODDs for lateral acceleration type 2: 0.2 g to 0.3 g (per 1,000 miles traveled).

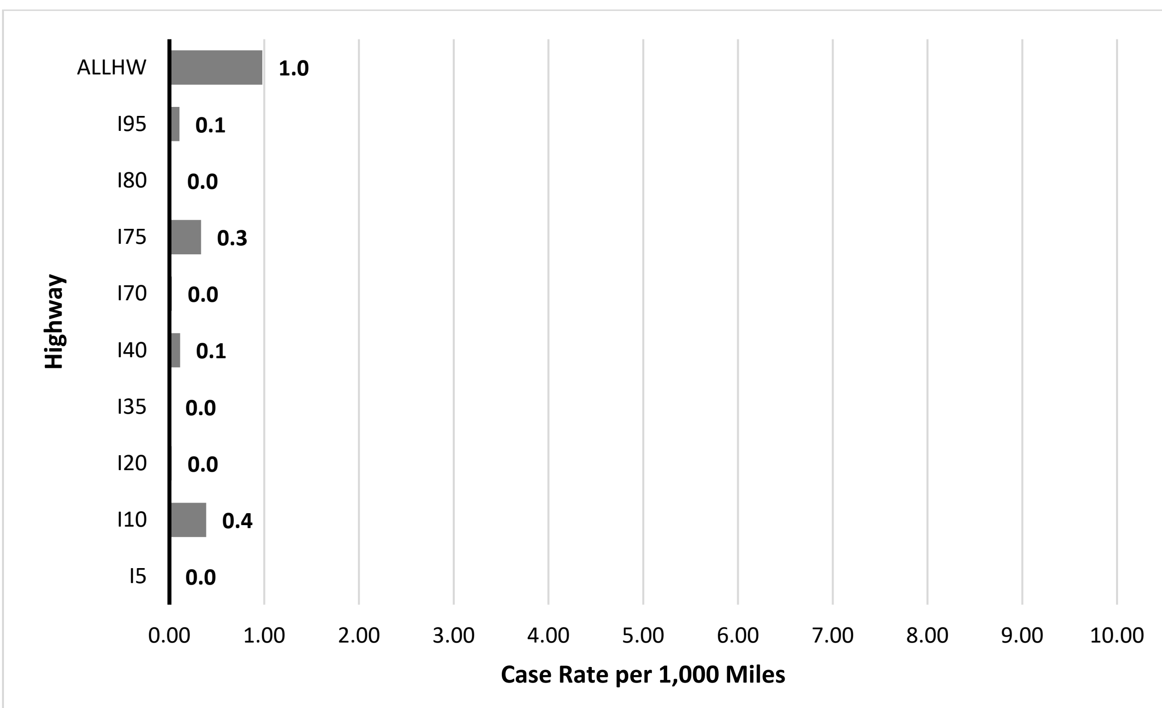

Figure 37. Chart. Case frequency in 10 highway ODDs for lateral acceleration type 3: 0.3 g to 0.35 g (per 1,000 miles traveled).

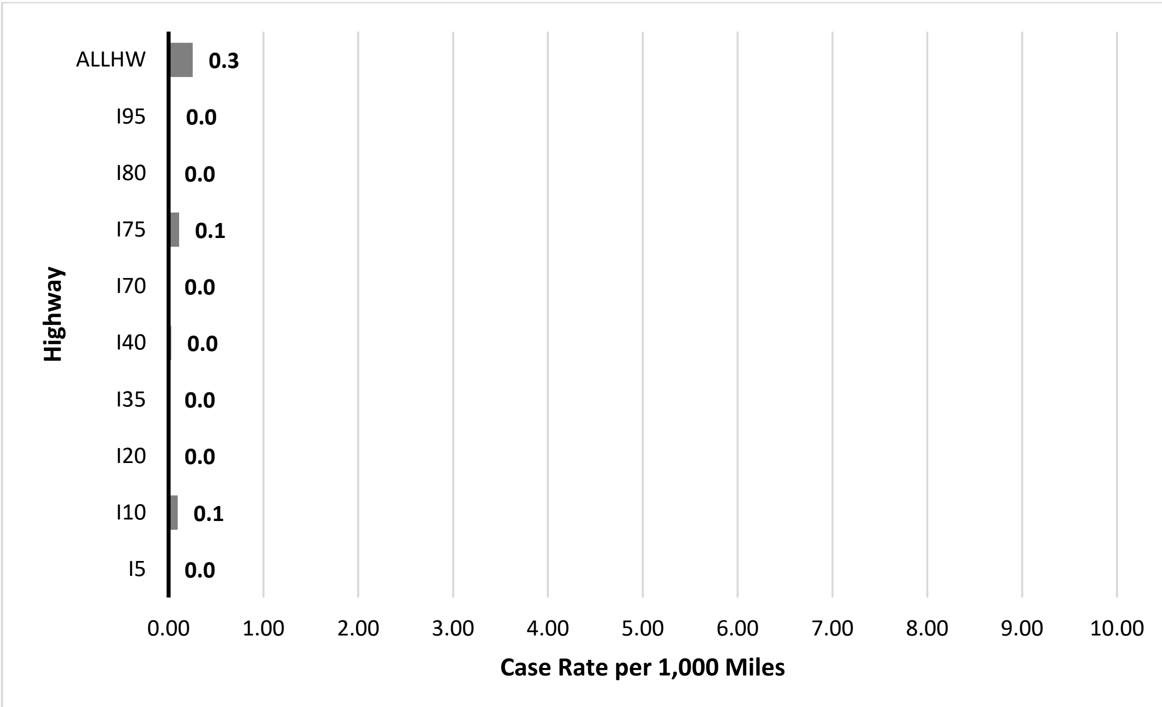

Figure 38. Chart. Case frequency in 10 highway ODDs for lateral acceleration type 4: greater than or equal to 0.35 g (per 1,000 miles traveled).

Lateral Acceleration Behavior by Speed Limit ODD

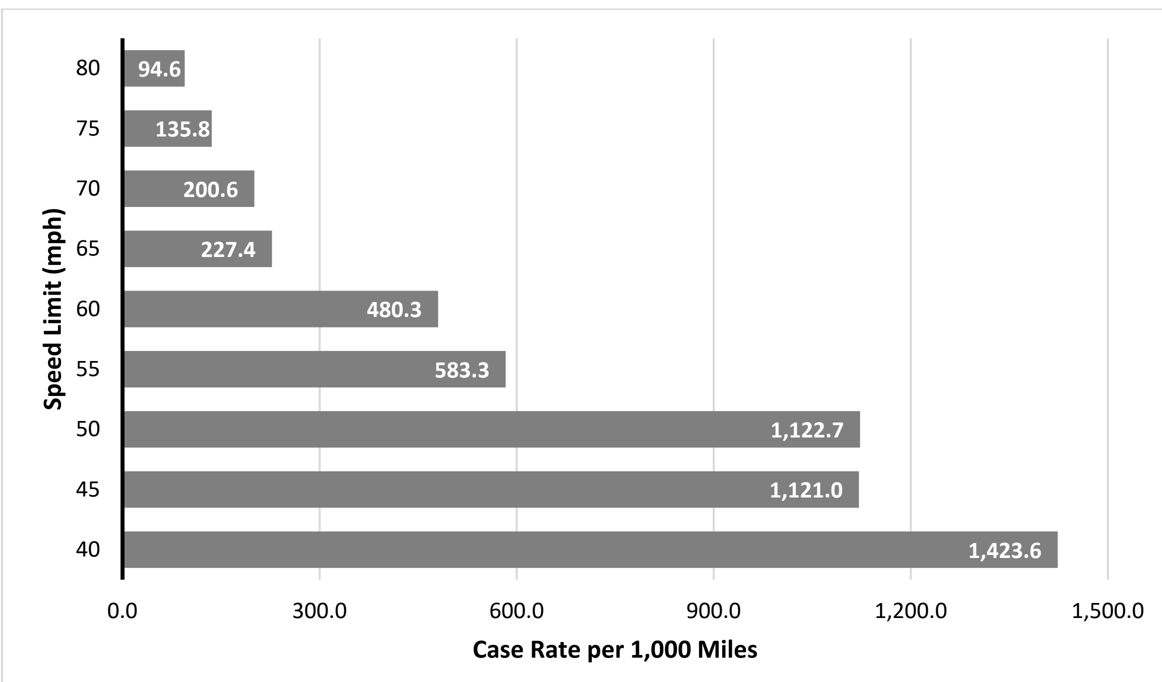

Figure 39. Chart. Case frequency in nine speed limit ODDs for lateral acceleration type 1: 0.1 g to 0.2 g (per 1,000 miles traveled).

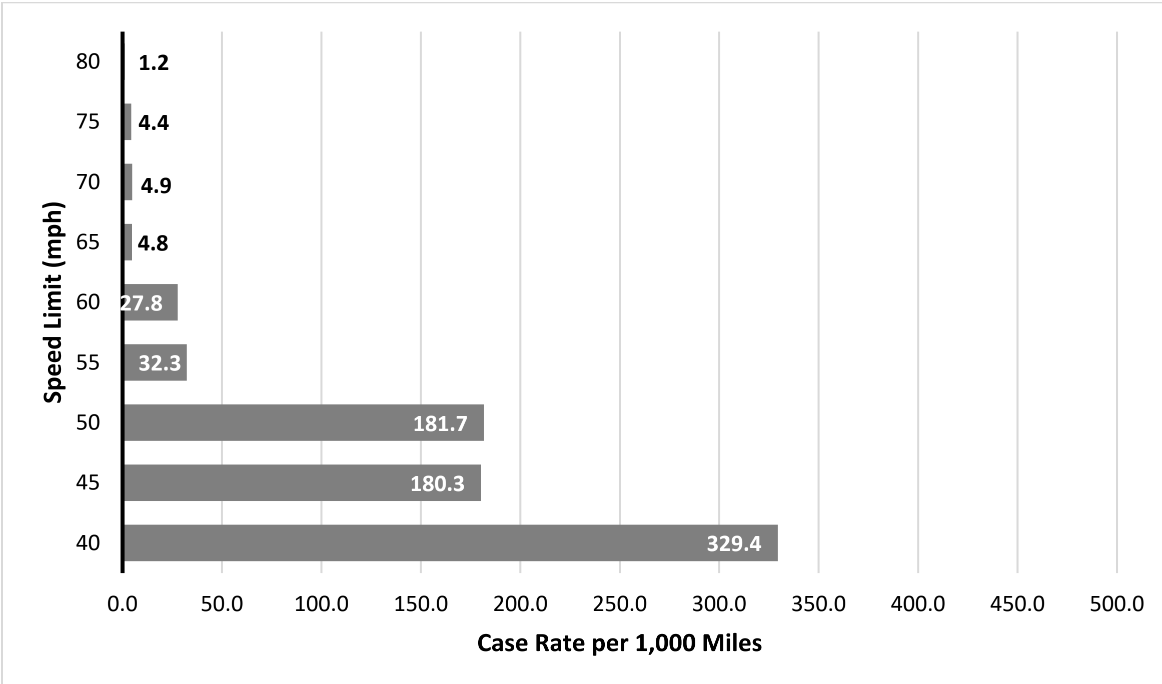

Figure 40. Chart. Case frequency in nine speed limit ODDs for lateral acceleration type 2: 0.2 g to 0.3 g (per 1,000 miles traveled).

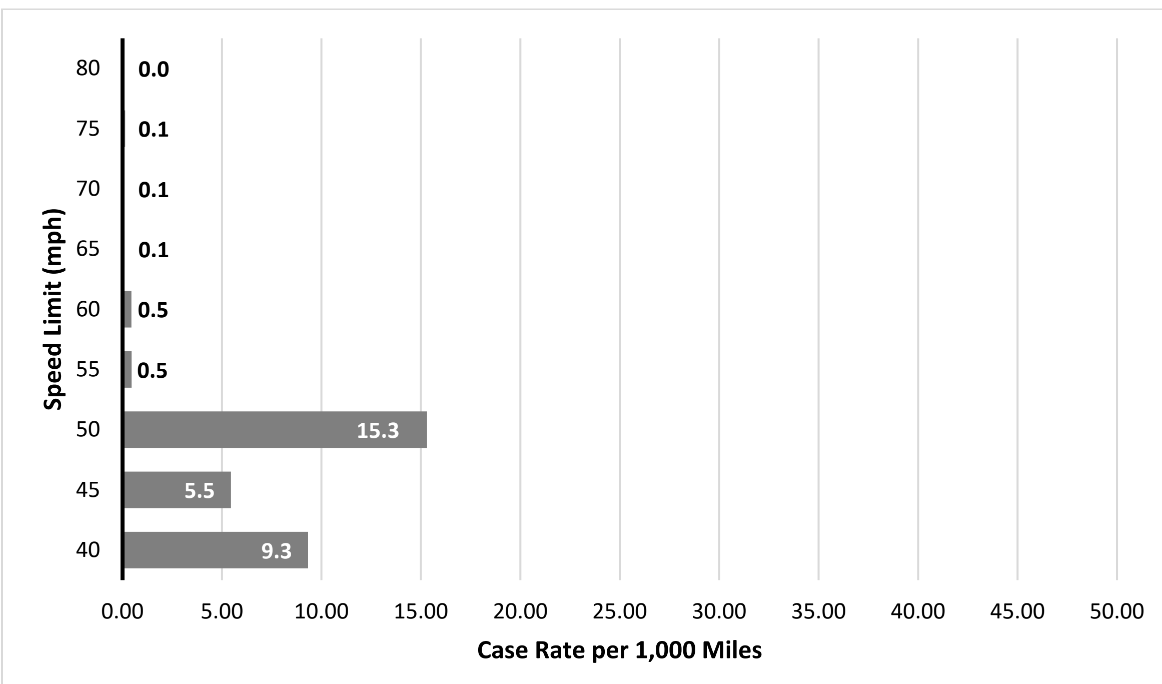

Figure 41. Chart. Case frequency rate in nine speed limit ODDs for lateral acceleration type 3: 0.3 g to 0.35 g (per 1,000 miles traveled).

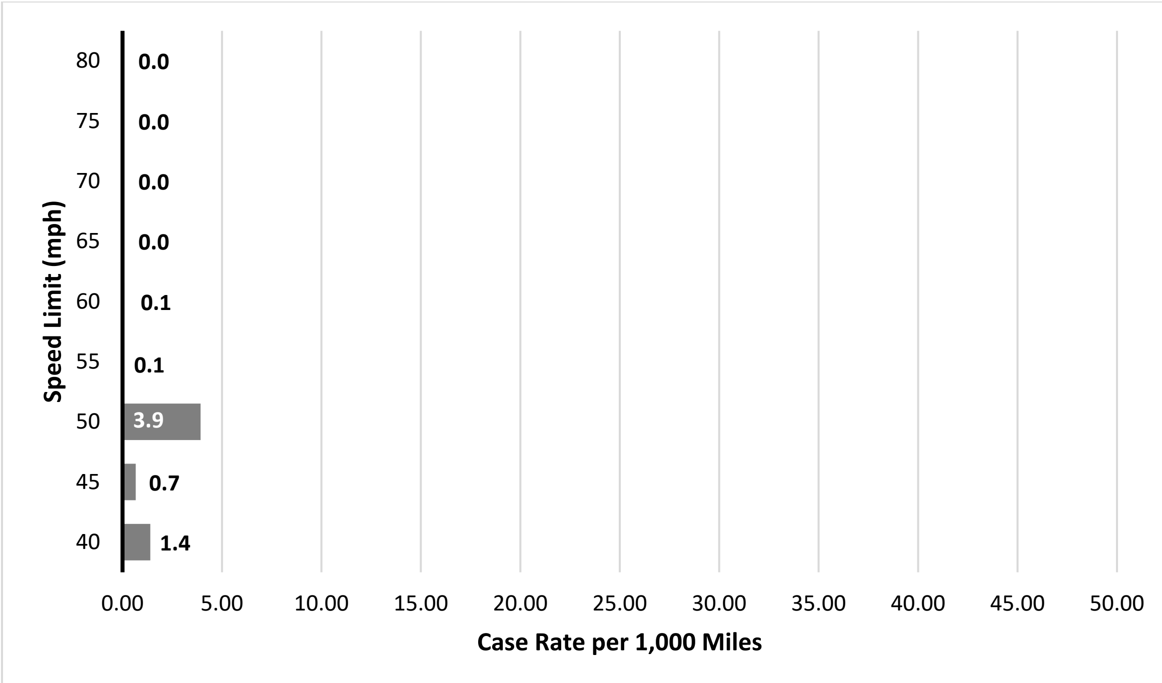

Figure 42. Chart. Case frequency rate in 9 speed limit ODDs for lateral acceleration type 4: greater than or equal to 0.35 g (per 1,000 miles traveled).

Lateral Acceleration Behavior by Number of Lanes

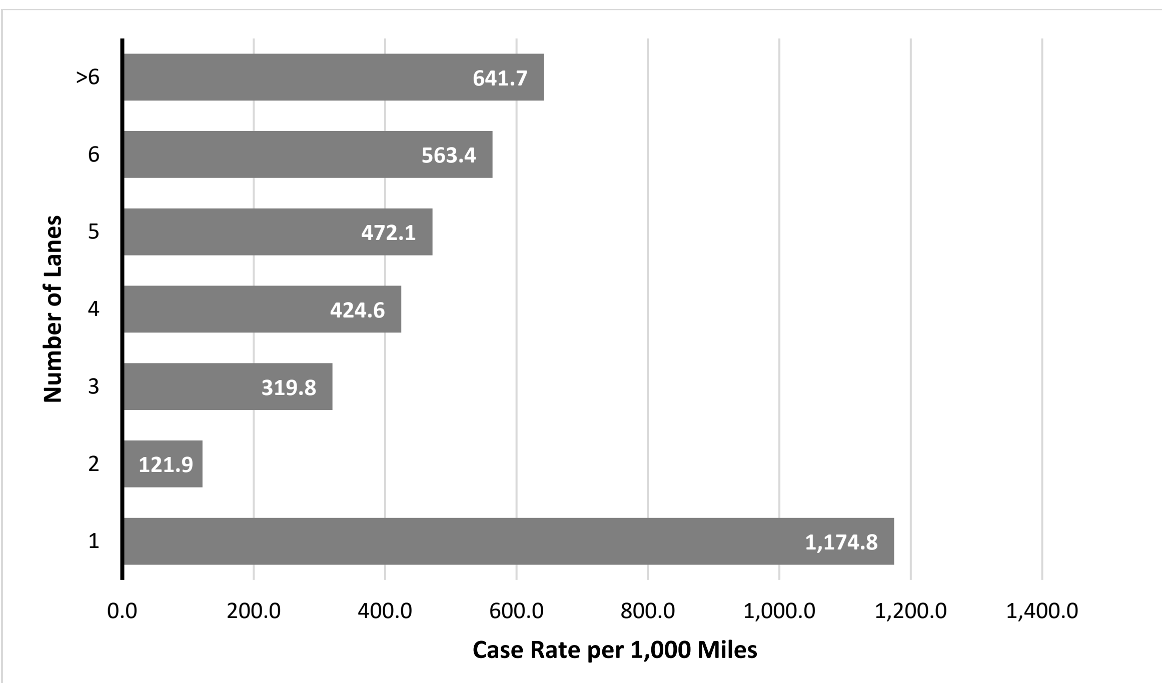

Figure 43. Chart. Case rate by number of lanes for lateral acceleration type 1: 0.1 g to 0.2 g (per 1,000 miles traveled).

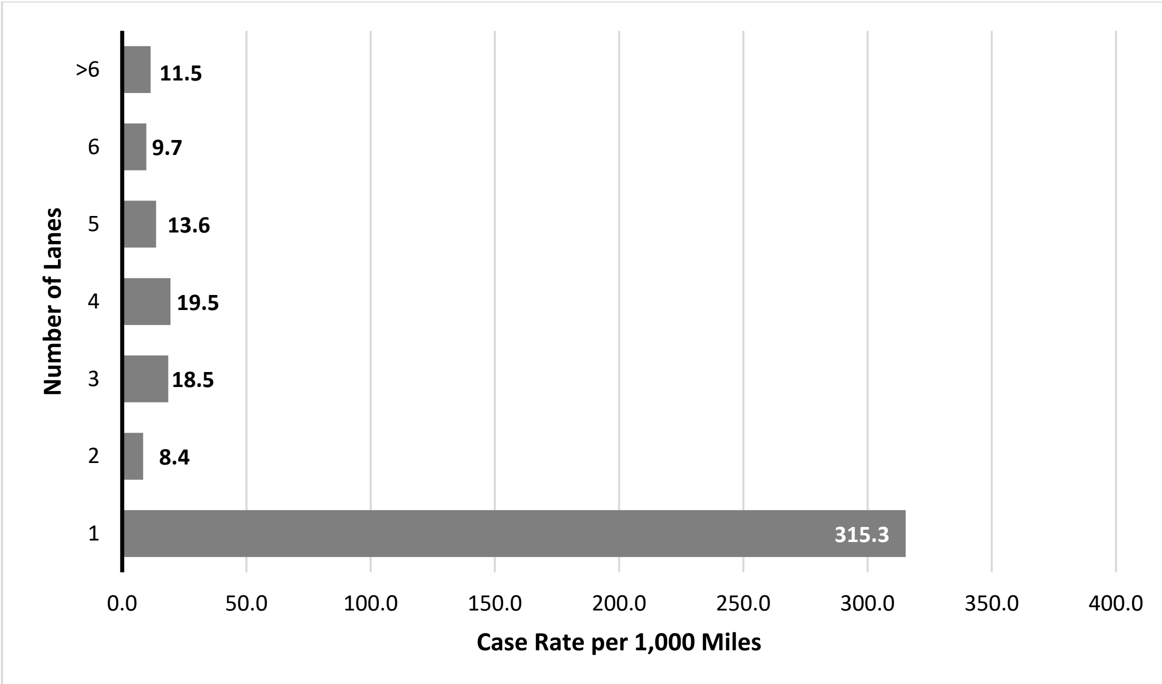

Figure 44. Chart. Case rate by number of lanes for lateral acceleration type 2: 0.2 g to 0.3 g (per 1,000 miles traveled).

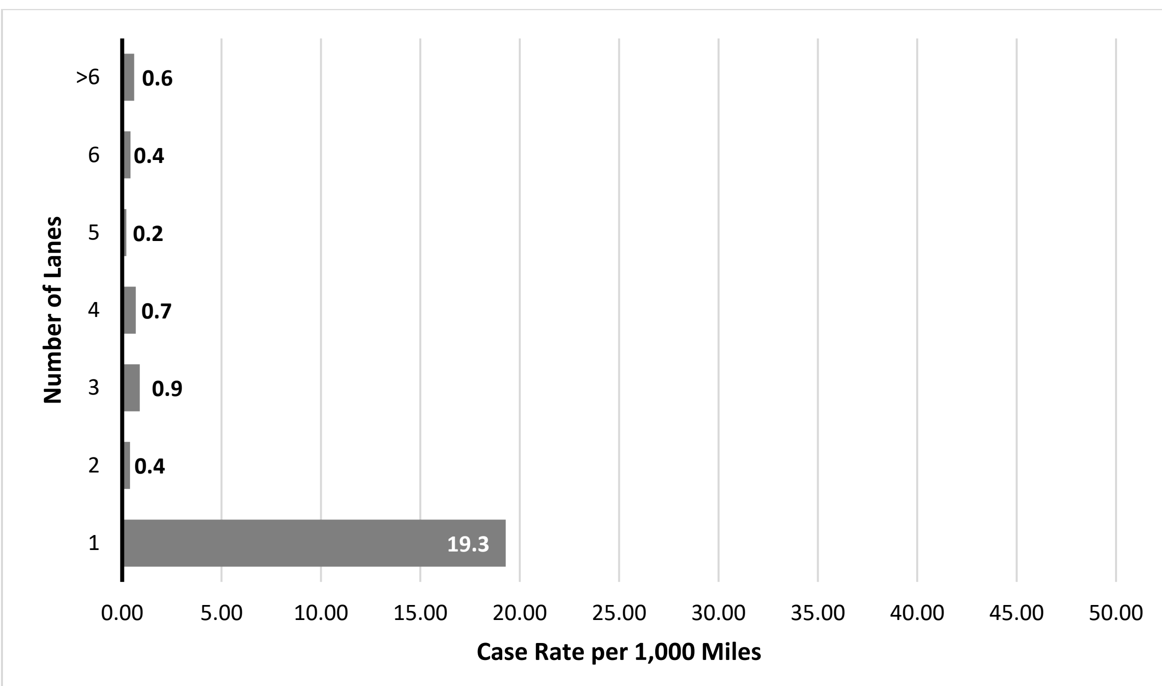

Figure 45. Chart. Case rate by number of lanes for lateral acceleration type 3: 0.3 g to 0.35 g (per 1,000 miles traveled).

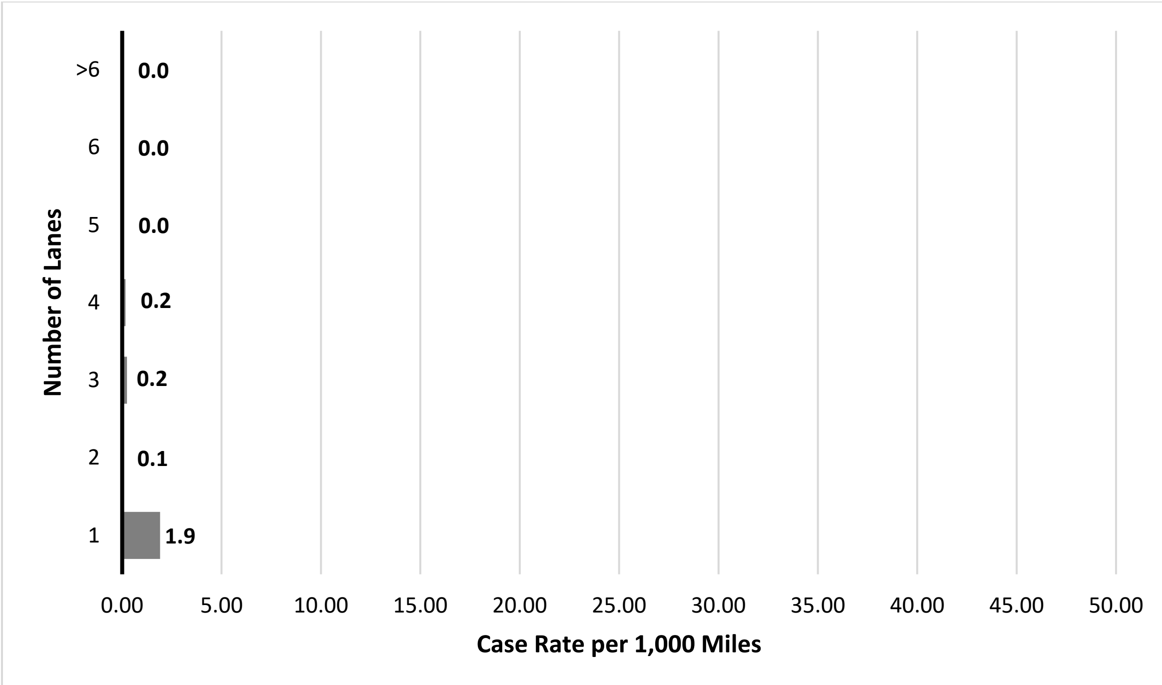

Figure 46. Chart. Case rate by number of lanes for lateral acceleration type 4: greater than or equal to 0.35 g (per 1,000 miles traveled).

LONGITUDINAL DECELERATION

Longitudinal Deceleration by Highway ODD

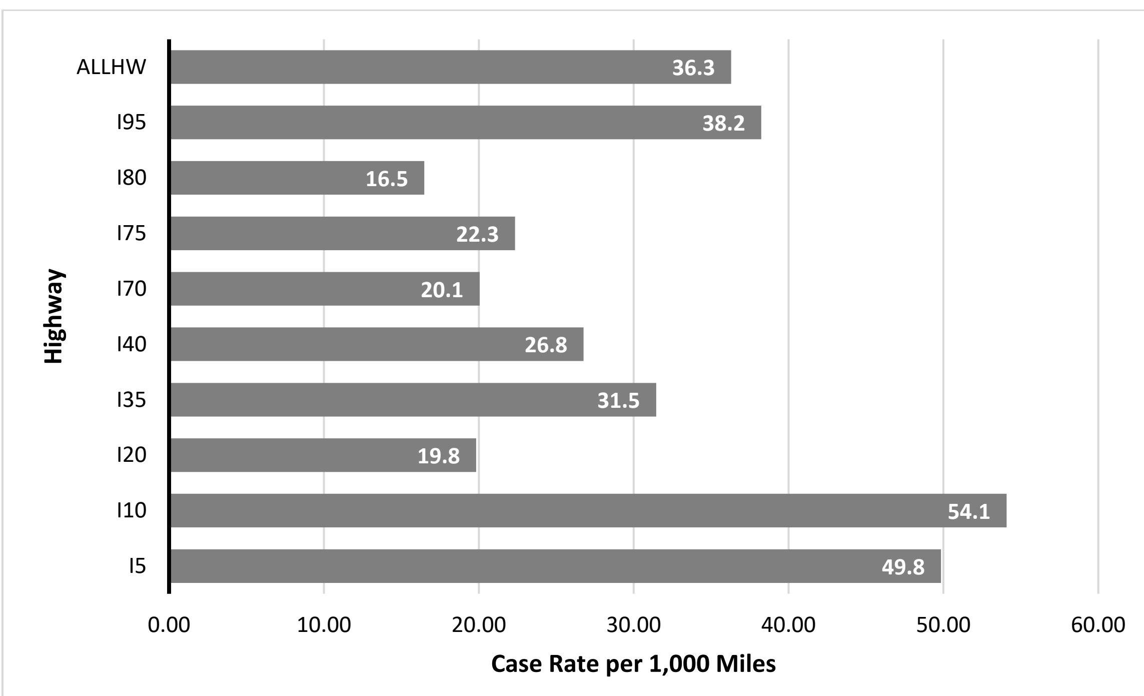

Figure 47. Chart. Case frequency in 10 highway ODDs for longitudinal deceleration type 1: 0.1 g to 0.2 g (per 1,000 miles traveled).

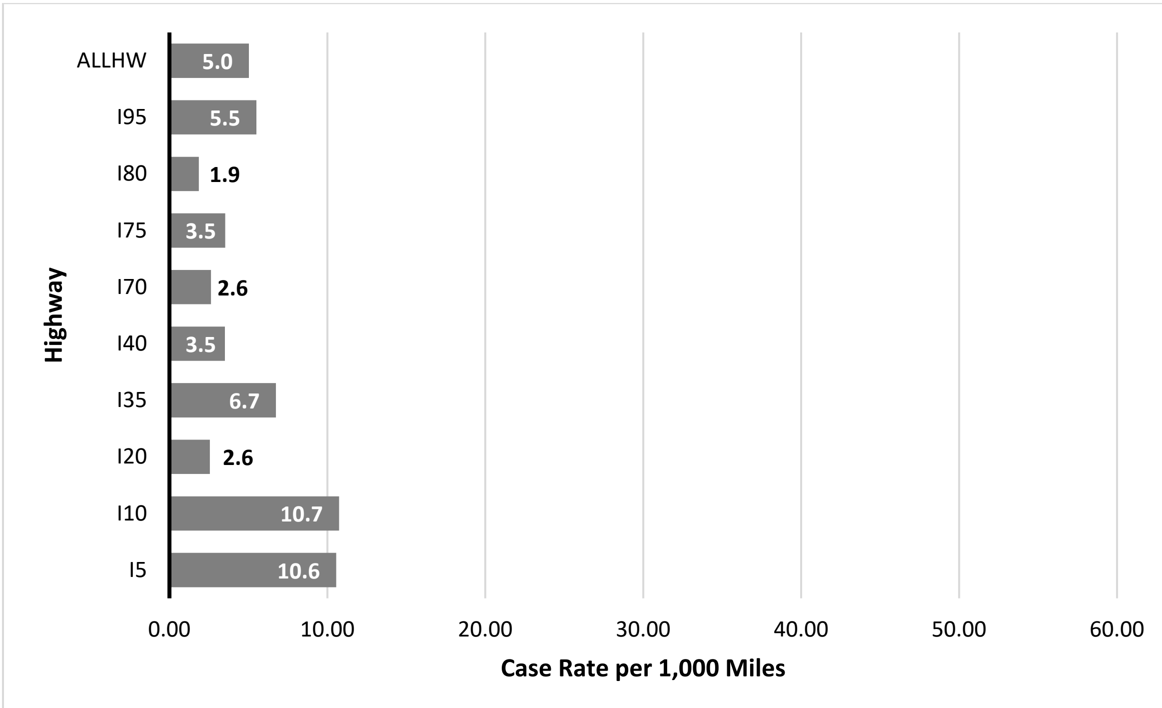

Figure 48. Chart. Case frequency in 10 highway ODDs for longitudinal deceleration type 2: 0.2 g to 0.35 g (per 1,000 miles traveled).

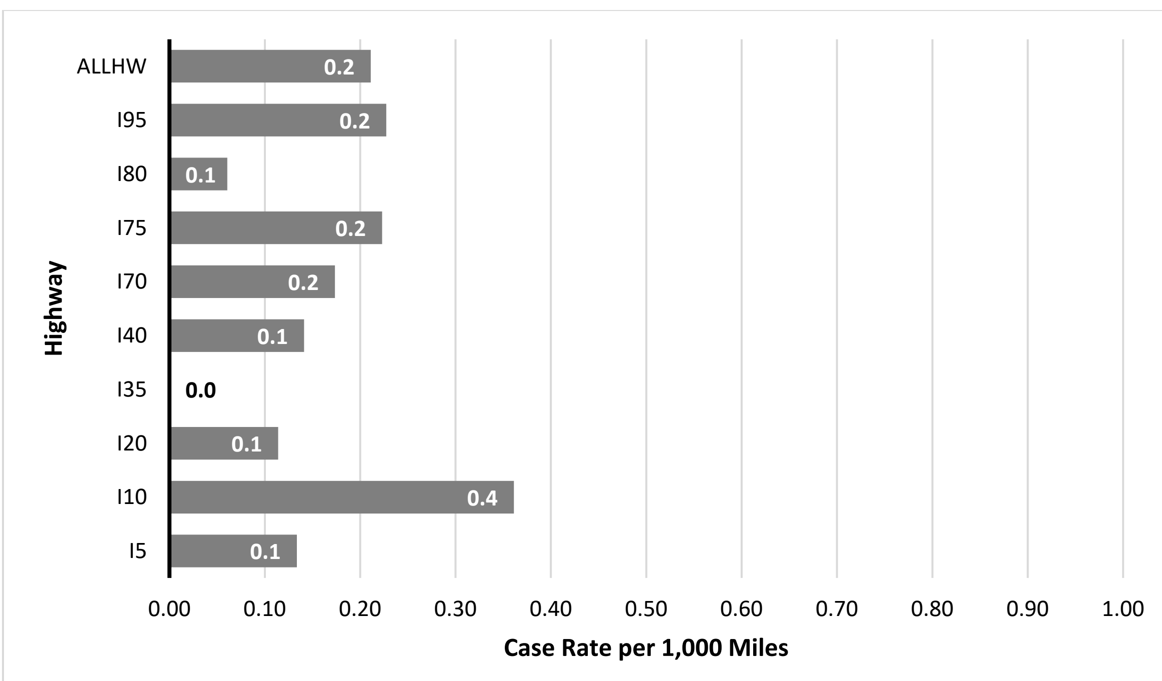

Figure 49. Chart. Case frequency in 10 highway ODDs for longitudinal deceleration type 3: greater than or equal to 0.35 g (per 1,000 miles traveled).

Longitudinal Deceleration by Speed Limit ODD

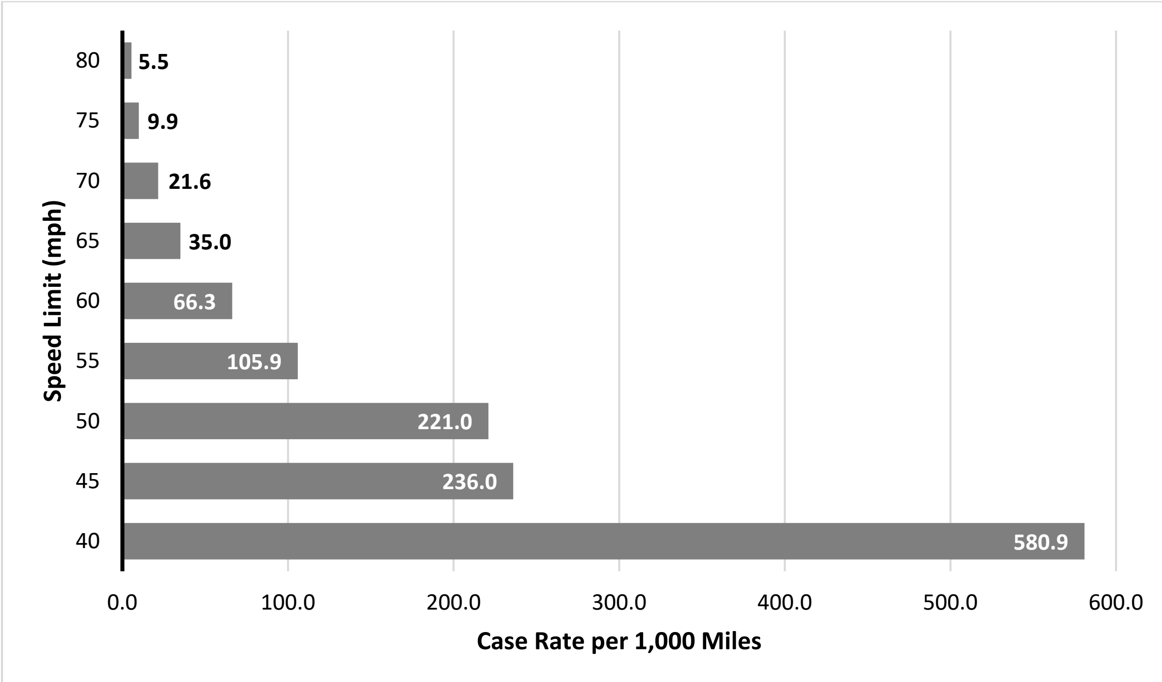

Figure 50. Chart. Case frequency by speed limit ODDs for longitudinal deceleration type 1: 0.1 g to 0.2 g (per 1,000 miles traveled).

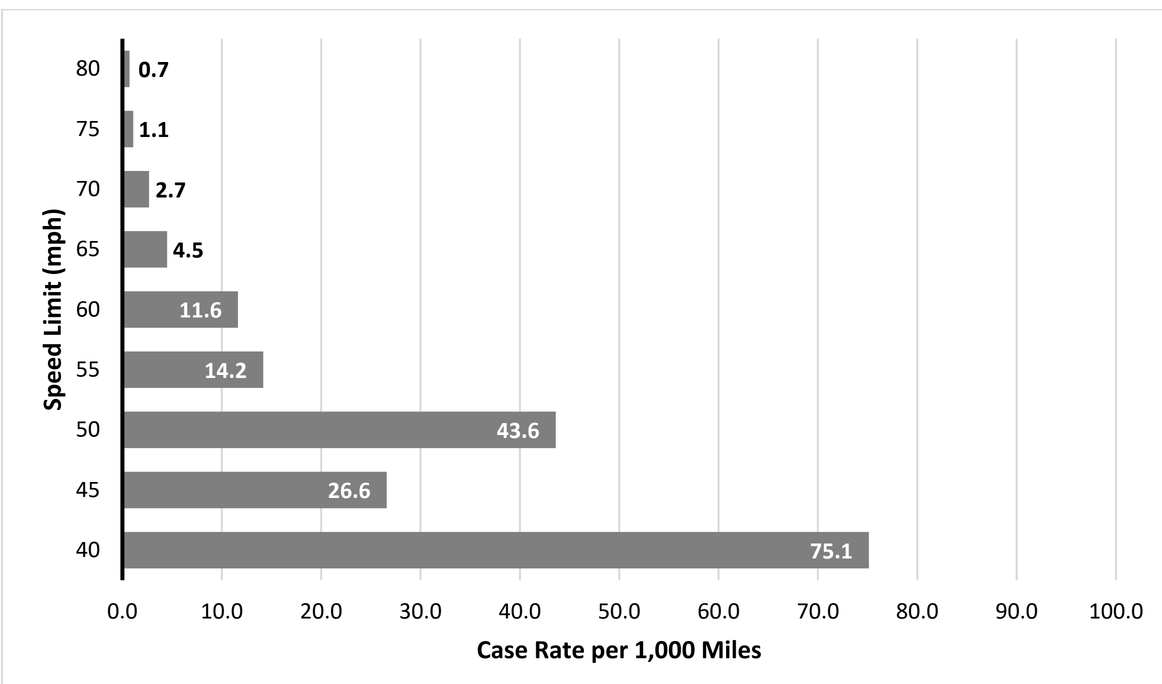

Figure 51. Chart. Case frequency by speed limit ODDs for longitudinal deceleration type 2: 0.2 g to 0.35 g (per 1,000 miles traveled).

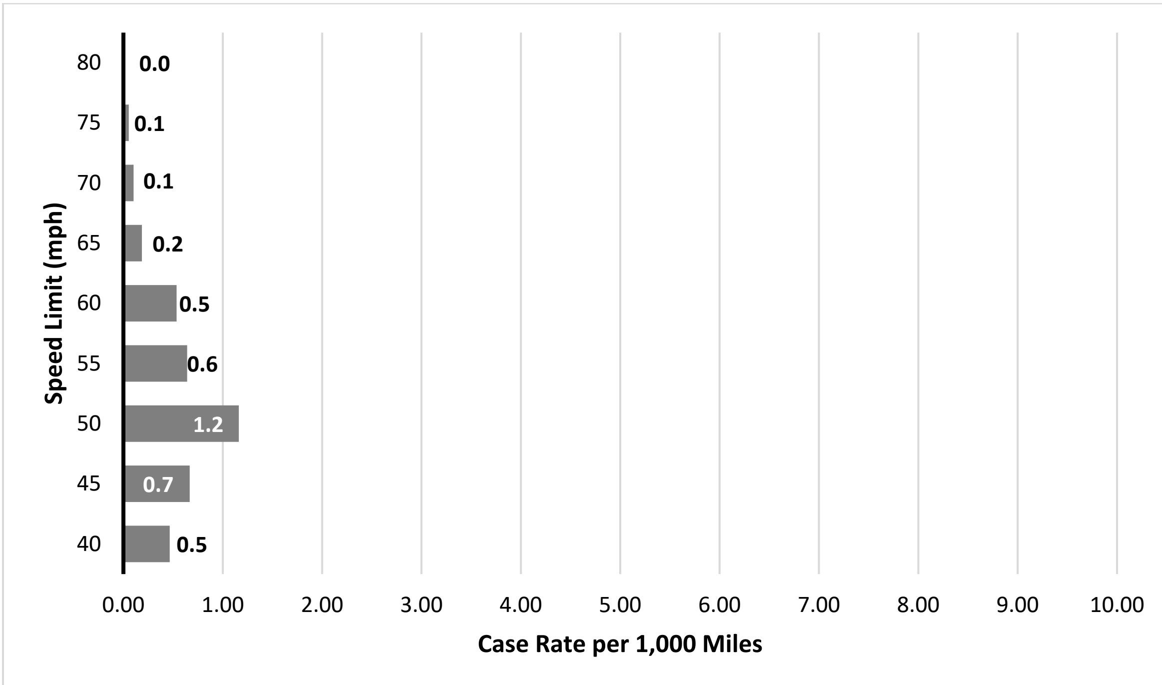

Figure 52. Chart. Case frequency by speed limit ODDs for longitudinal deceleration type 3: greater than or equal to 0.35 g (per 1,000 miles traveled).

Longitudinal Deceleration Behavior by Number of Lanes

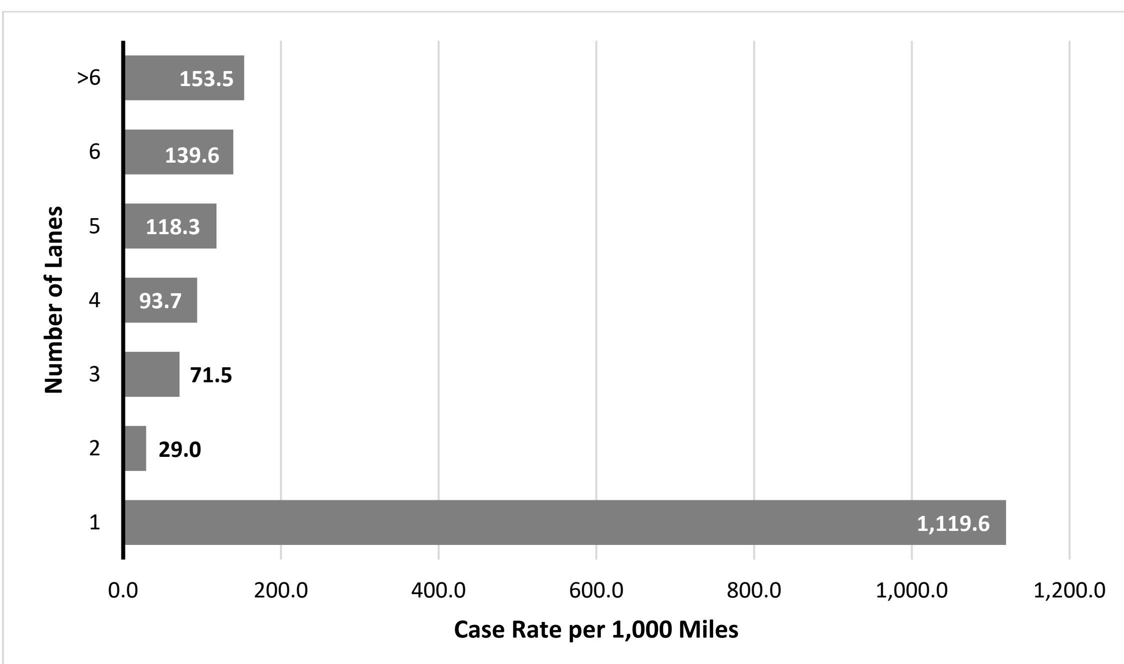

Figure 53. Chart. Case rates by number of lanes for longitudinal deceleration type 1: 0.1 g to 0.2 g (per 1,000 miles traveled).

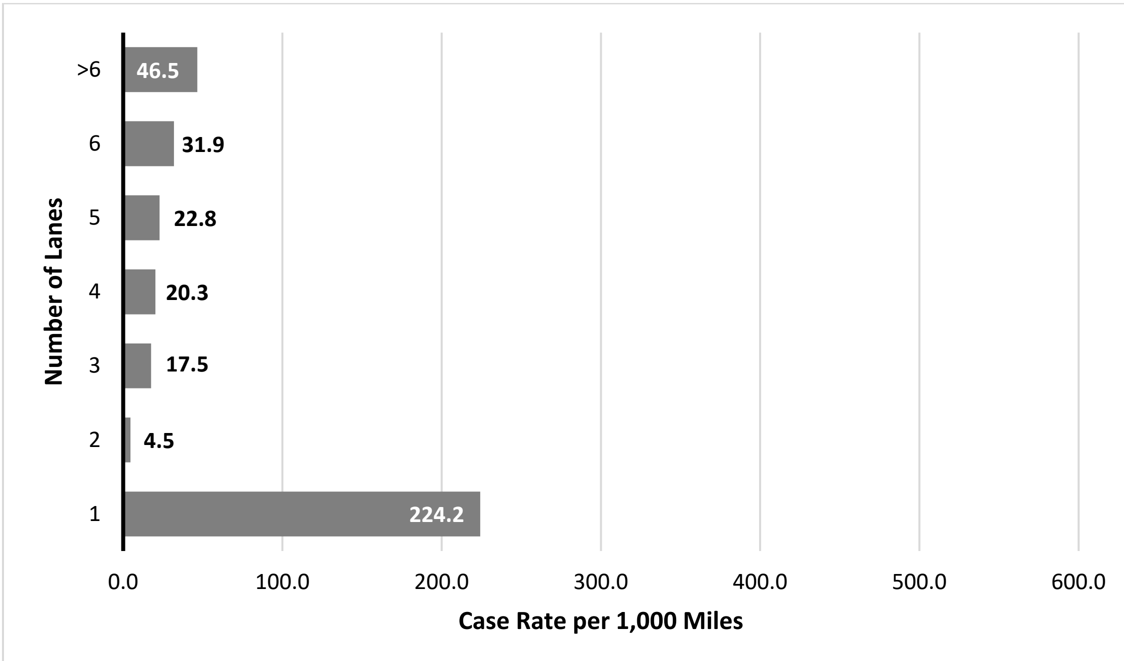

Figure 54. Chart. Case rates by number of lanes for longitudinal deceleration type 2: 0.2 g to 0.35 g (per 1,000 miles traveled).

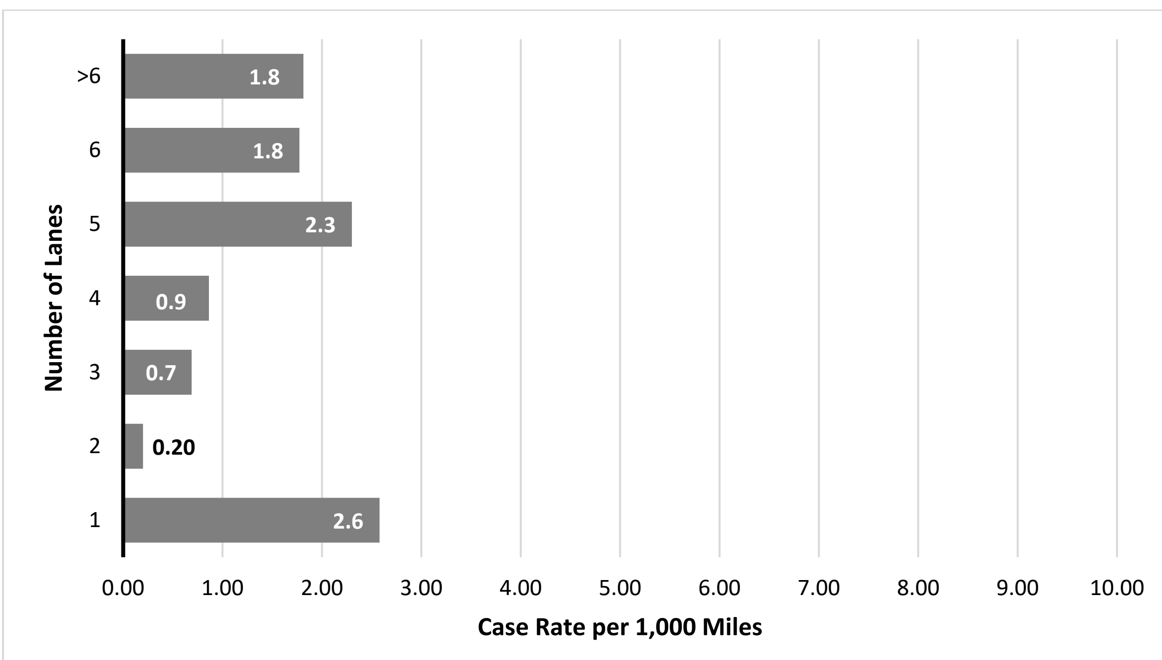

Figure 55. Chart. Case rates number of lanes for longitudinal deceleration type 3: greater than or equal to 0.35 g (per 1,000 miles traveled).

FOLLOWING DISTANCE

Following Distance Behavior by Highway ODD

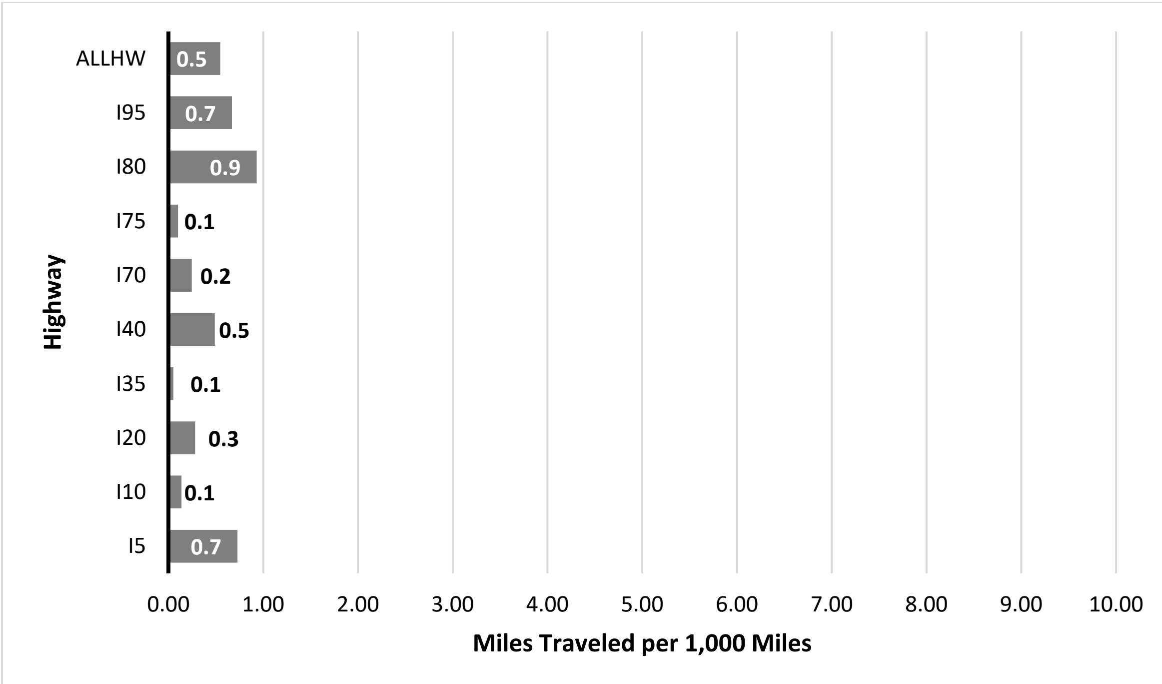

Figure 56. Chart. Highway miles traveled in 10 highway ODDs for following distance type 1: headway less than 1 second (per 1,000 miles traveled).

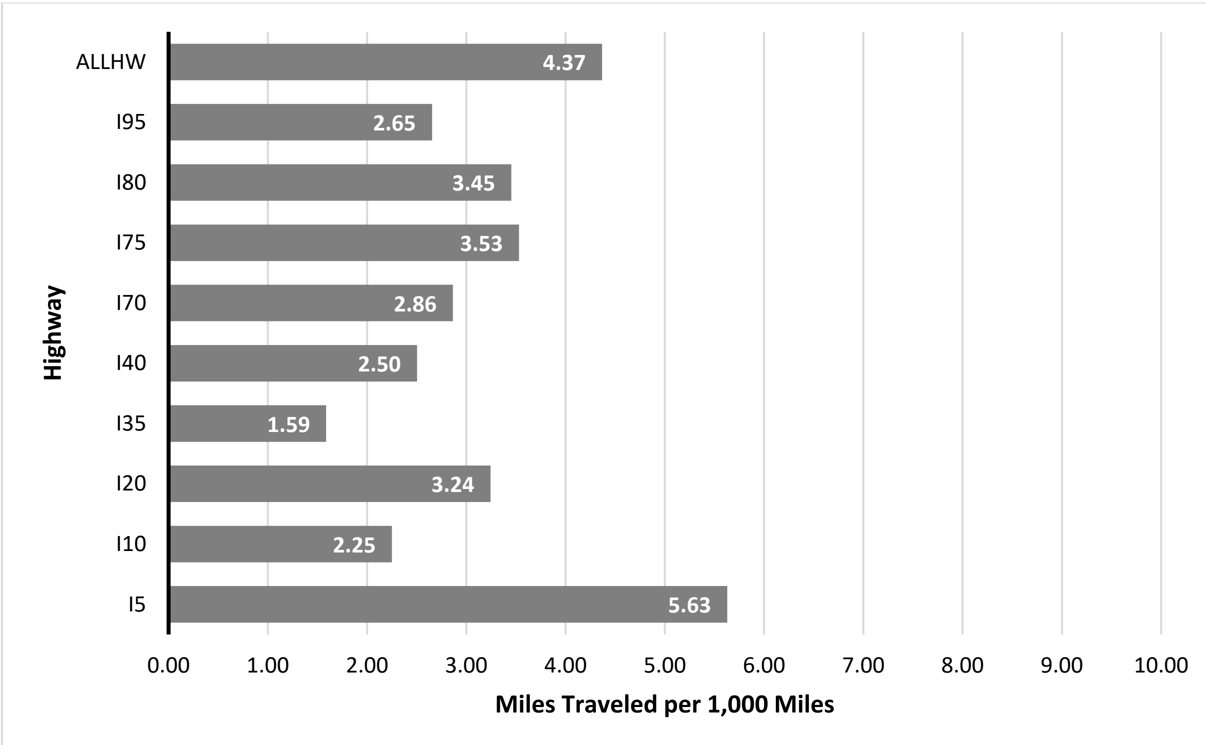

Figure 57. Chart. Highway miles traveled in 10 highway ODDs for following distance type 2: headway 1 to 2 seconds (per 1,000 miles traveled).

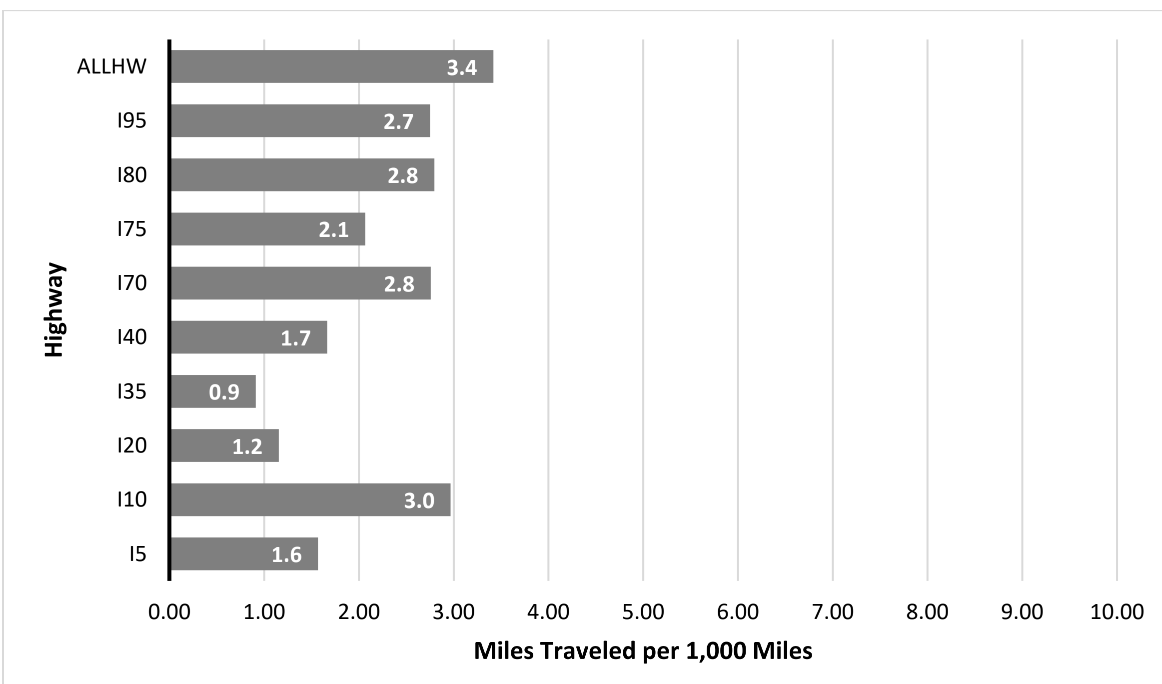

Figure 58. Chart. Highway miles traveled in 10 highway ODDs for following distance type 3: headway 2 to 3 seconds (per 1,000 miles traveled).

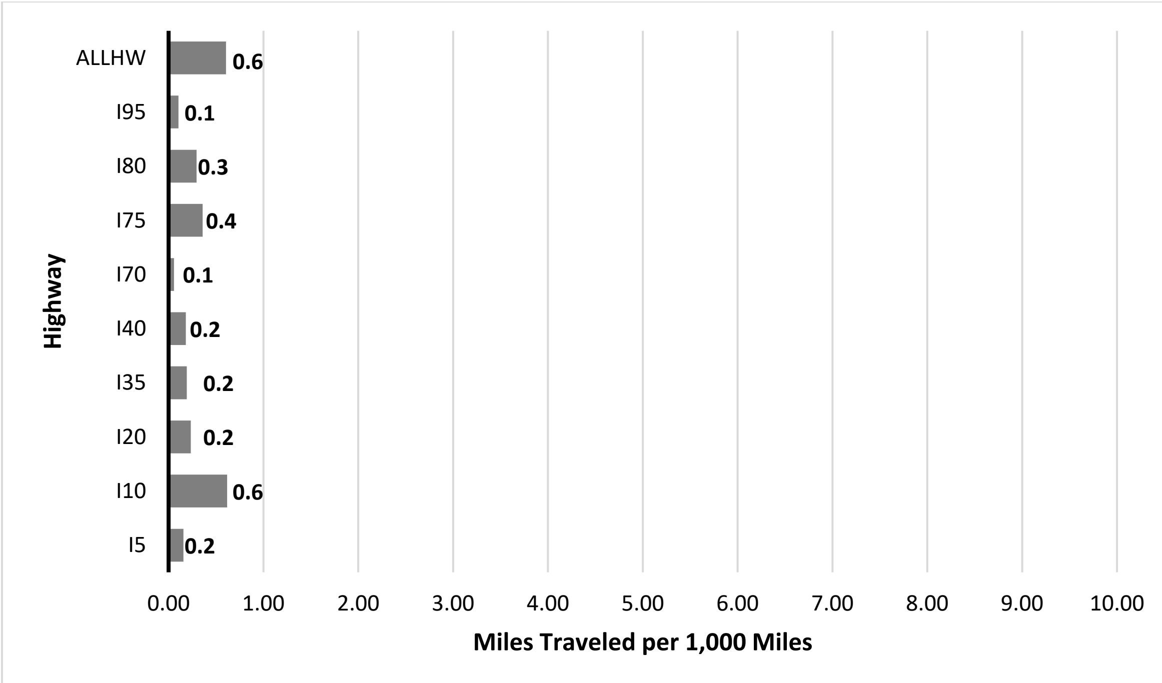

Figure 59. Chart. Highway miles traveled rate in 10 highway ODDs for following distance type 4: headway 3 to 4 seconds (per 1,000 miles traveled).

Following Distance Behavior by Speed Limit ODD

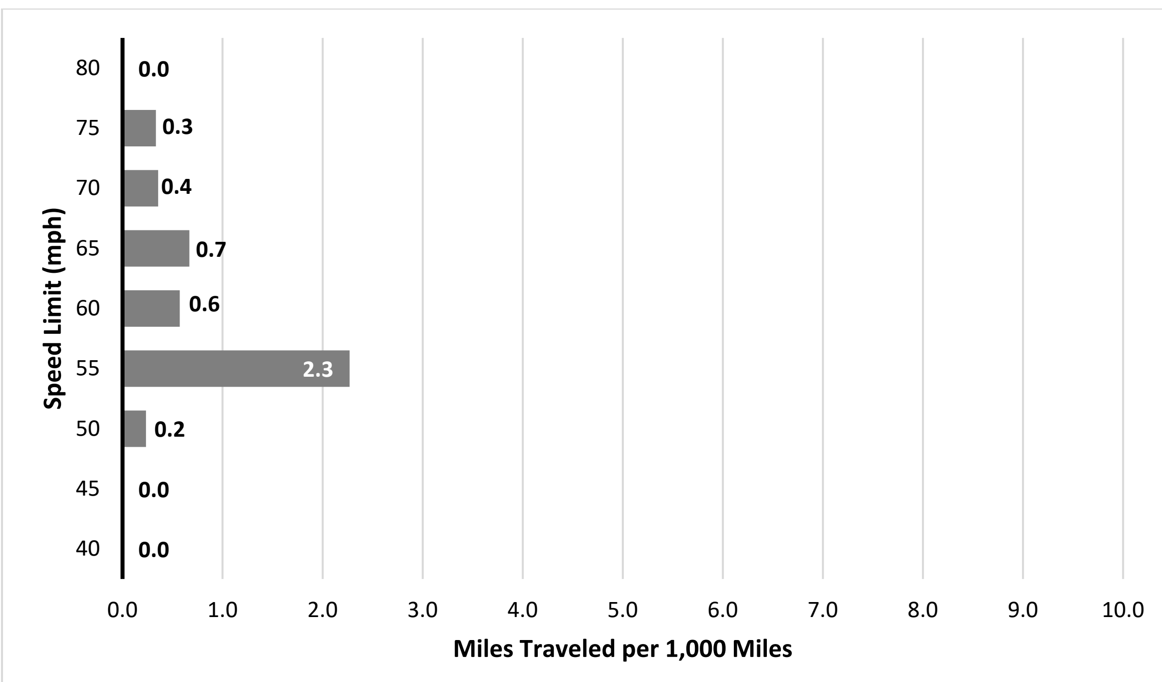

Figure 60. Chart. Highway miles traveled in speed limit ODDs for following distance type 1: headway less than 1 second (per 1,000 miles traveled).

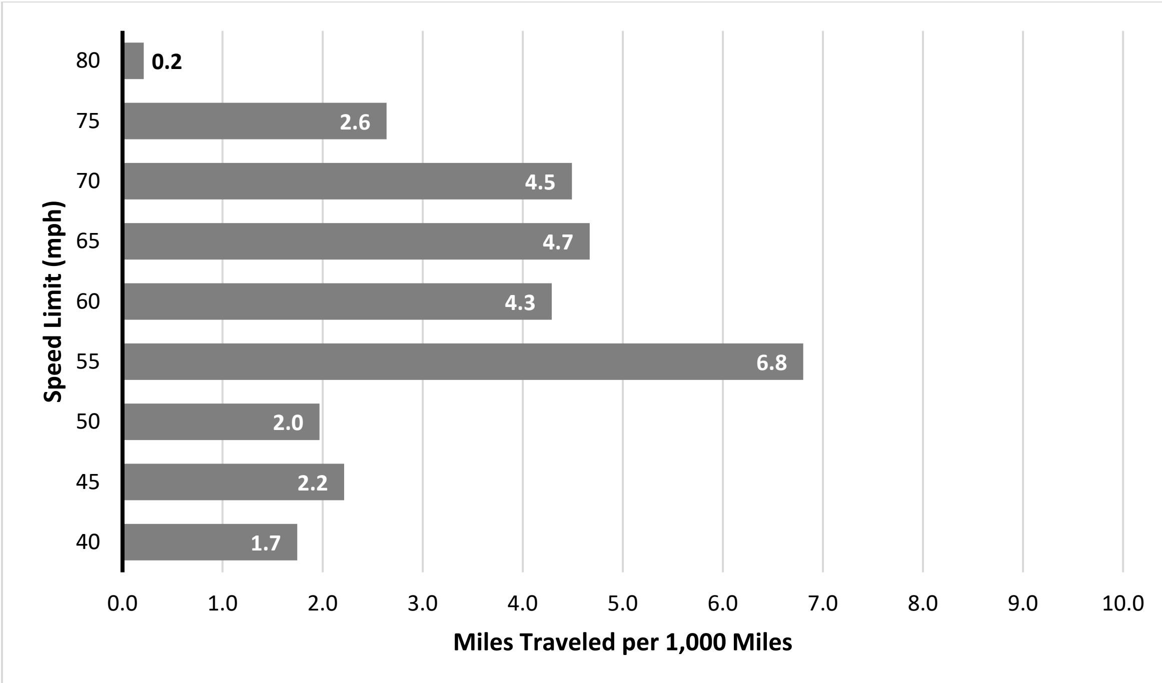

Figure 61. Chart. Case frequency rate in speed limit ODDs for following distance type 2: headway 1 to 2 seconds (per 1,000 miles traveled).

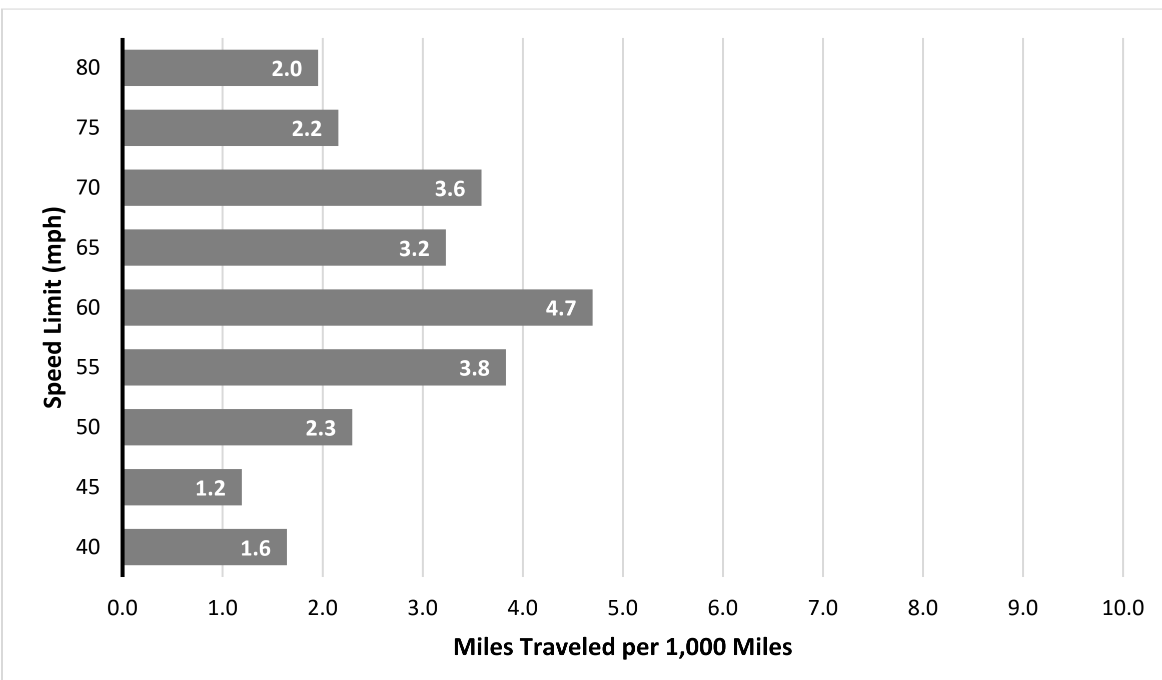

Figure 62. Chart. Highway miles traveled rate in speed limit ODDs for following distance type 3: headway 2 to 3 seconds (per 1,000 miles traveled).

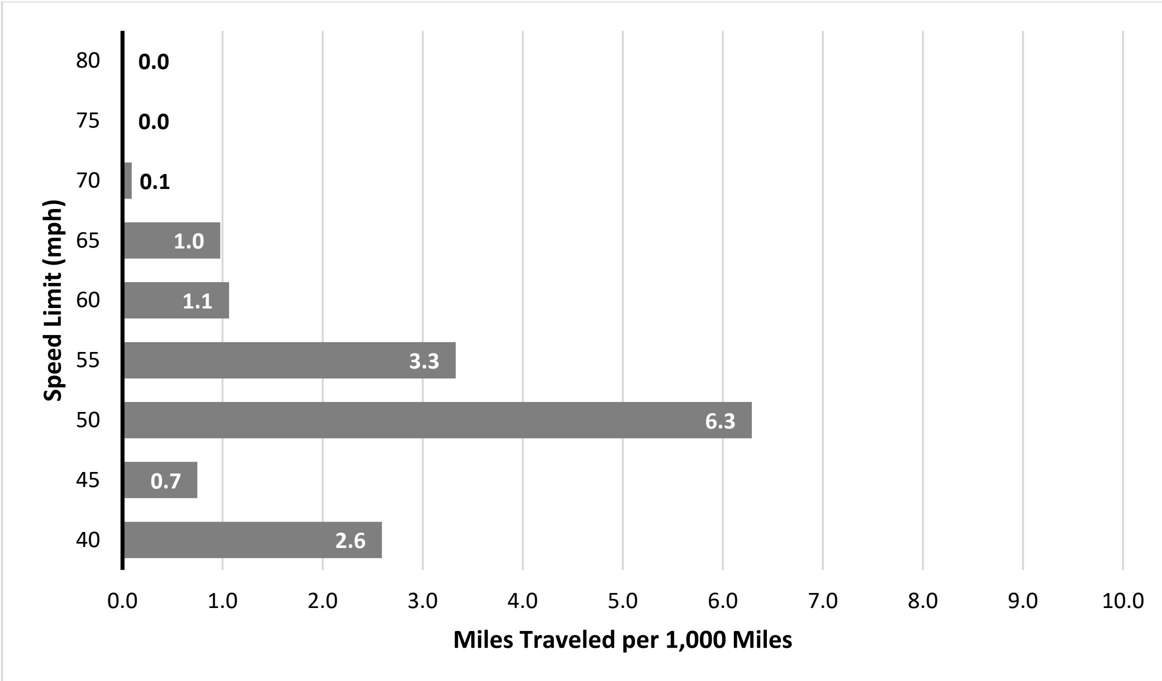

Figure 63. Chart. Case frequency rate in speed limit ODDs for following distance type 4: headway 3 to 4 seconds (per 1,000 miles traveled).

Following Distance Behavior by Number of Lanes

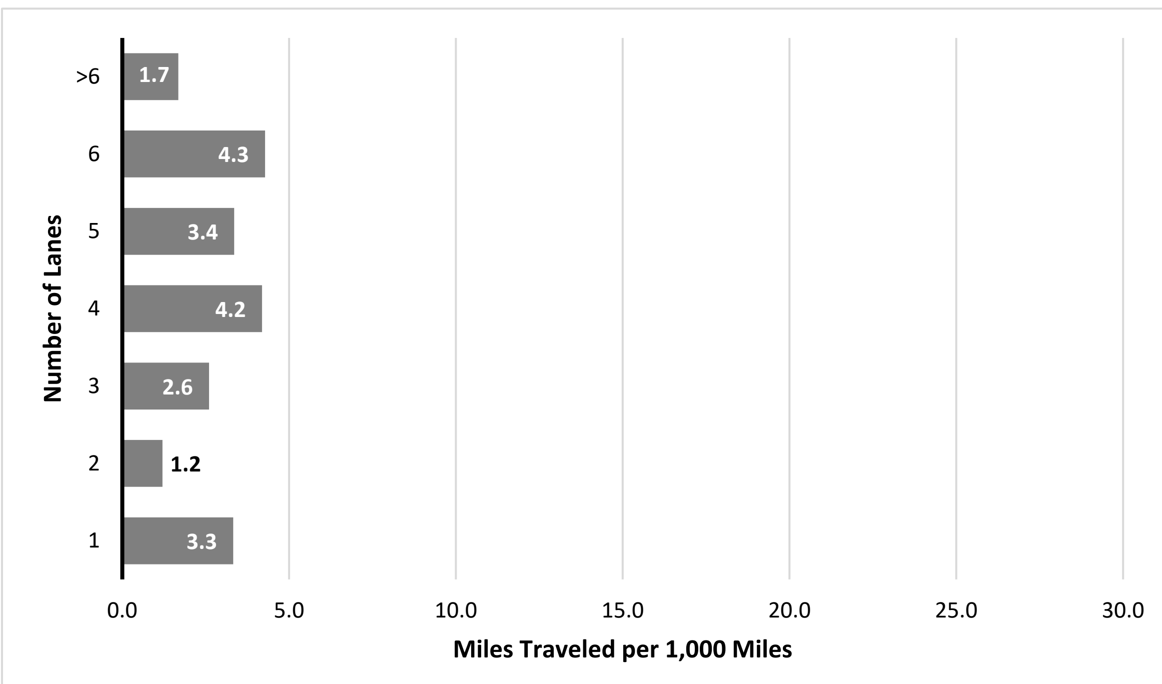

Figure 64. Chart. Highway miles traveled by number of lanes for following distance type 1: headway less than 1 second (per 1,000 miles traveled).

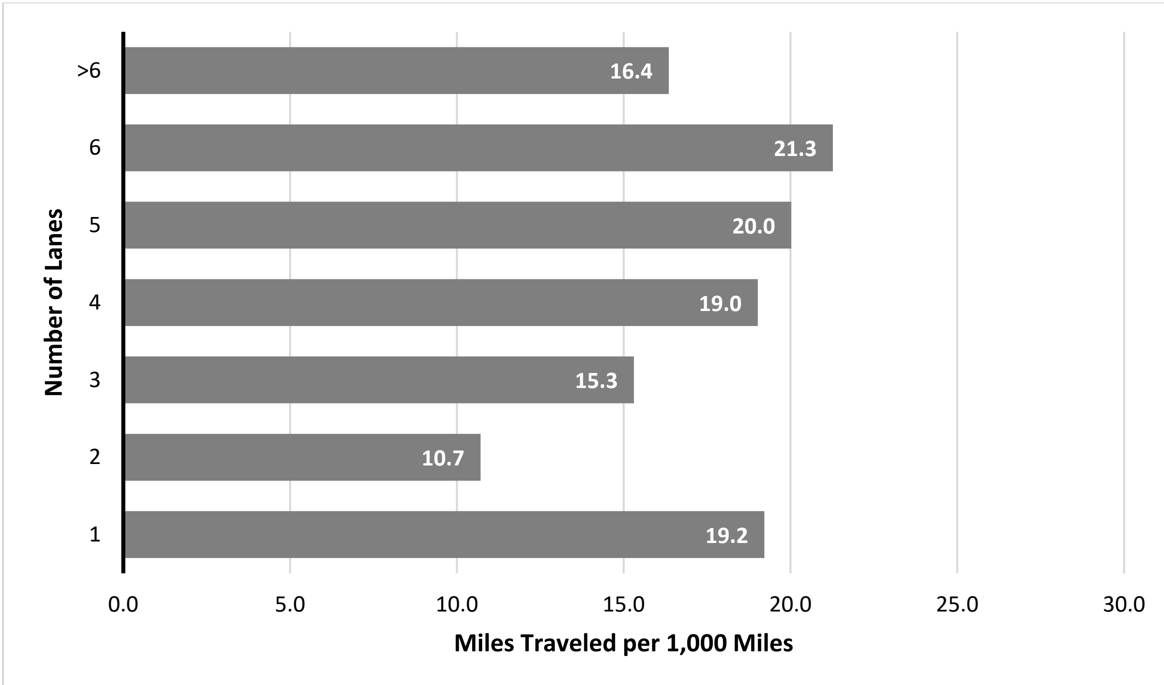

Figure 65. Chart. Highway miles traveled by number of lanes for following distance type 2: headway 1 to 2 seconds (per 1,000 miles traveled).

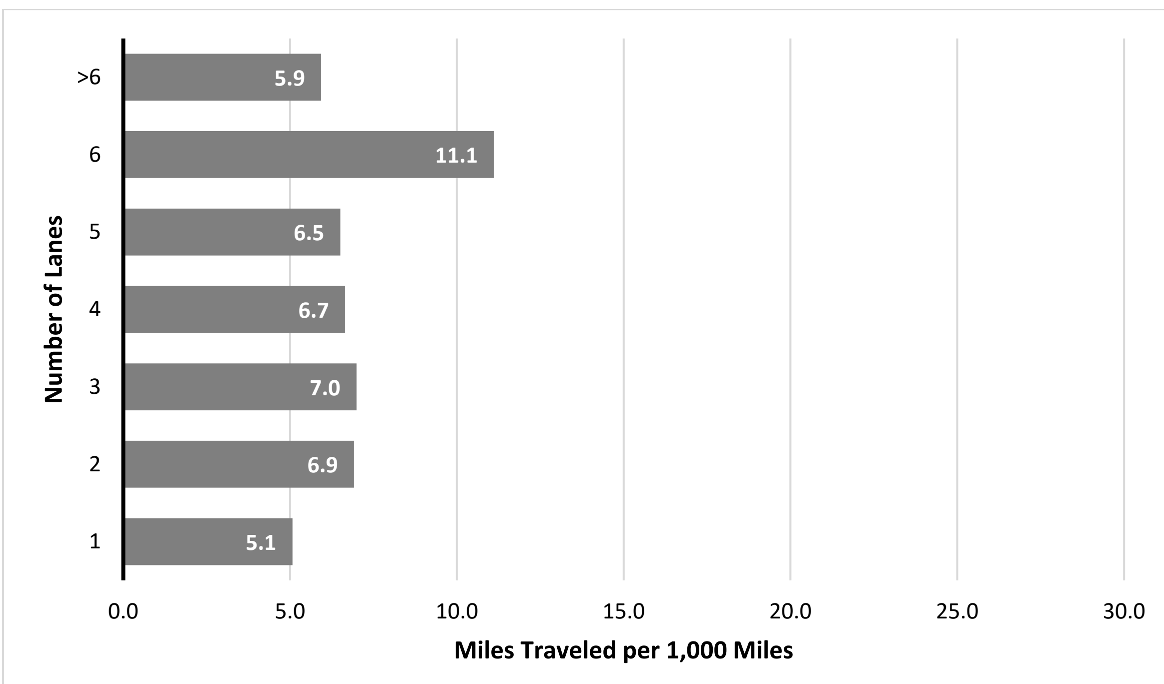

Figure 66. Chart. Highway miles traveled by number of lanes for following distance type 3: headway 2 to 3 seconds (per 1,000 miles traveled).

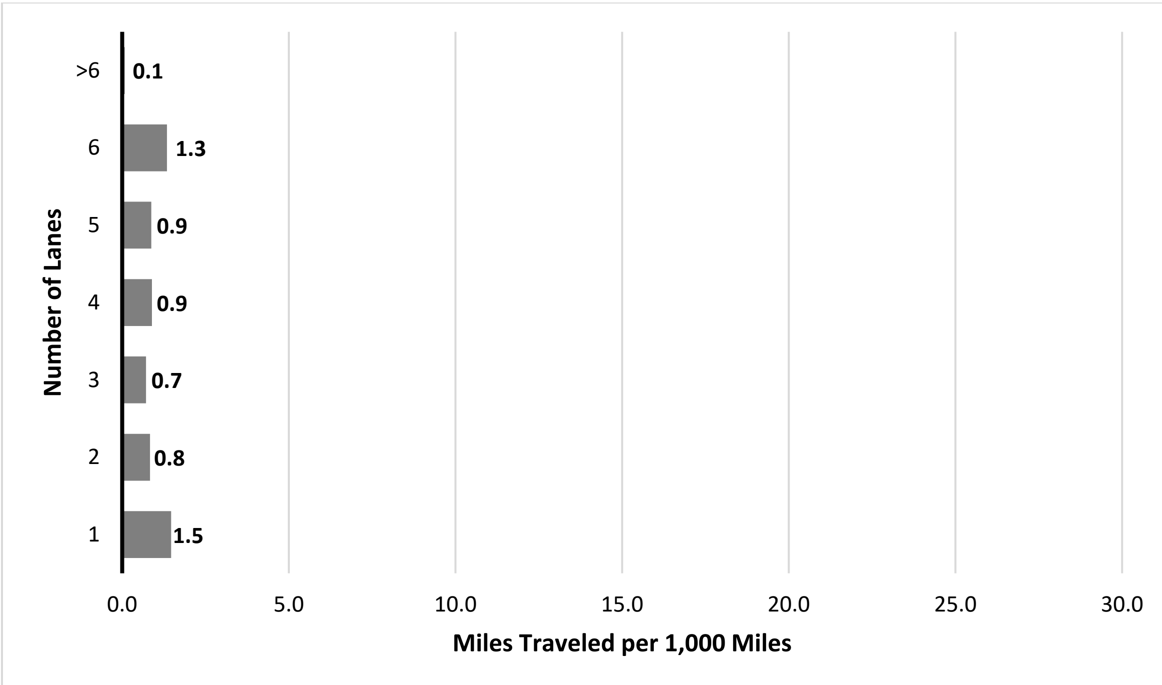

Figure 67. Chart. Highway miles traveled by number of lanes for following distance type 4: headway 3 to 4 seconds (per 1,000 miles traveled).

LANE DEVIATION

Land Deviation Behavior by Highway ODD

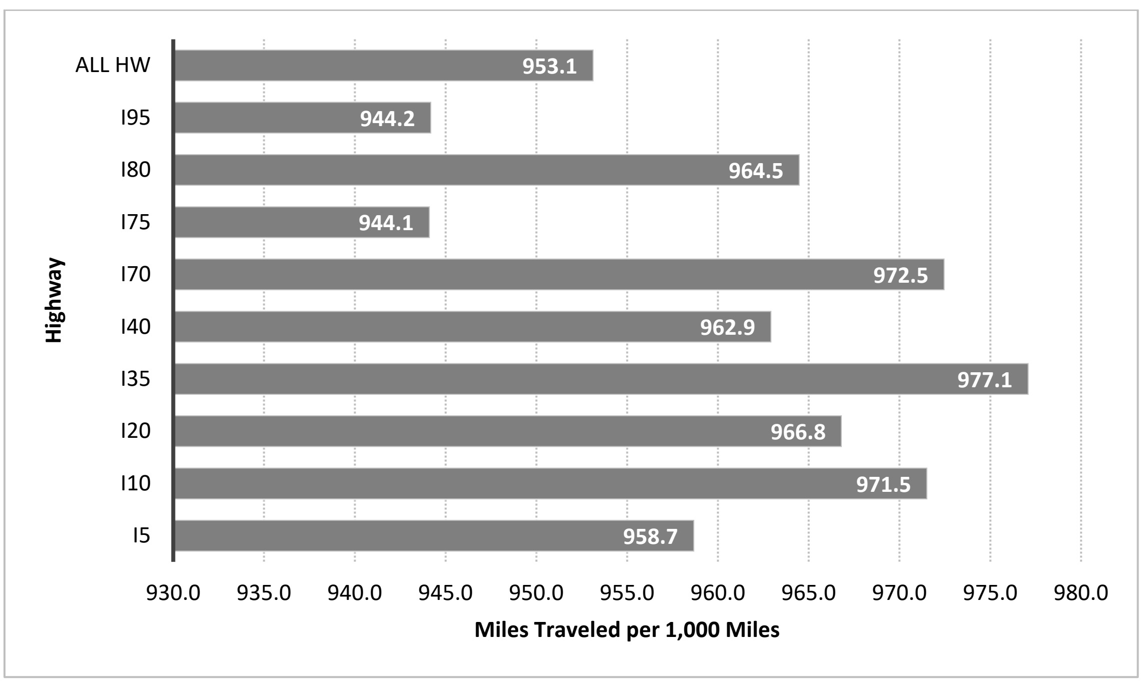

Figure 68. Chart. Highway miles traveled in highway ODDs for lane deviation type 1: 0-21 inches, inside lane (per 1,000 miles traveled).

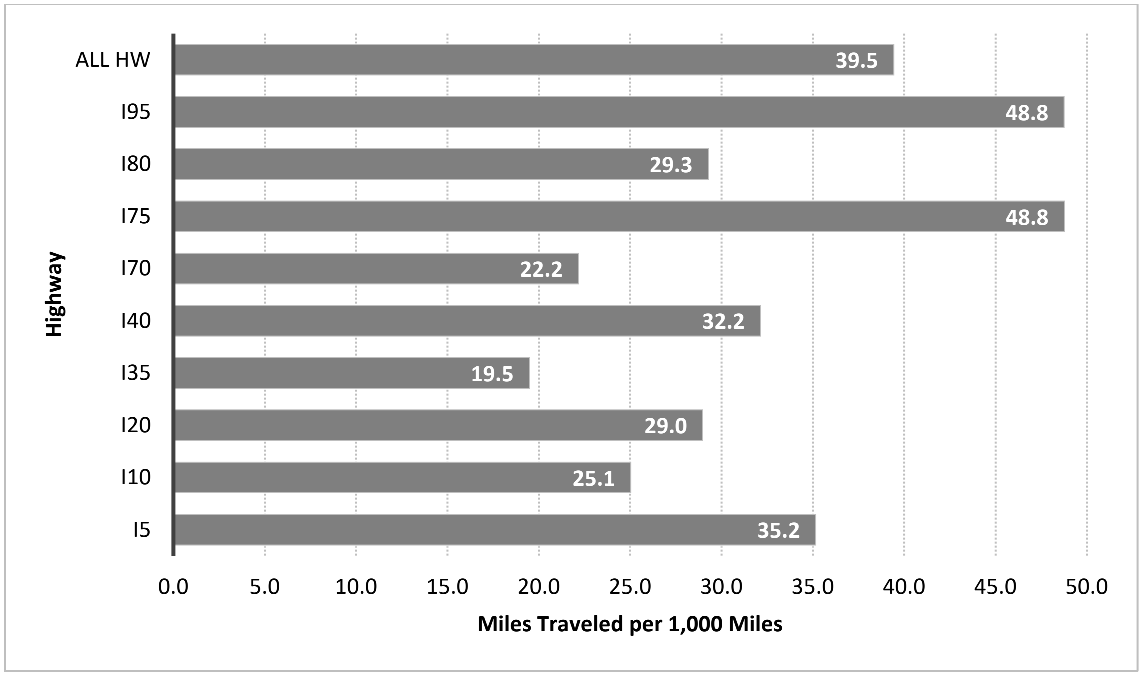

Figure 69. Chart. Highway miles traveled in highway ODDs for lane deviation type 2: 21-33 inches, outside lane (per 1,000 miles traveled).

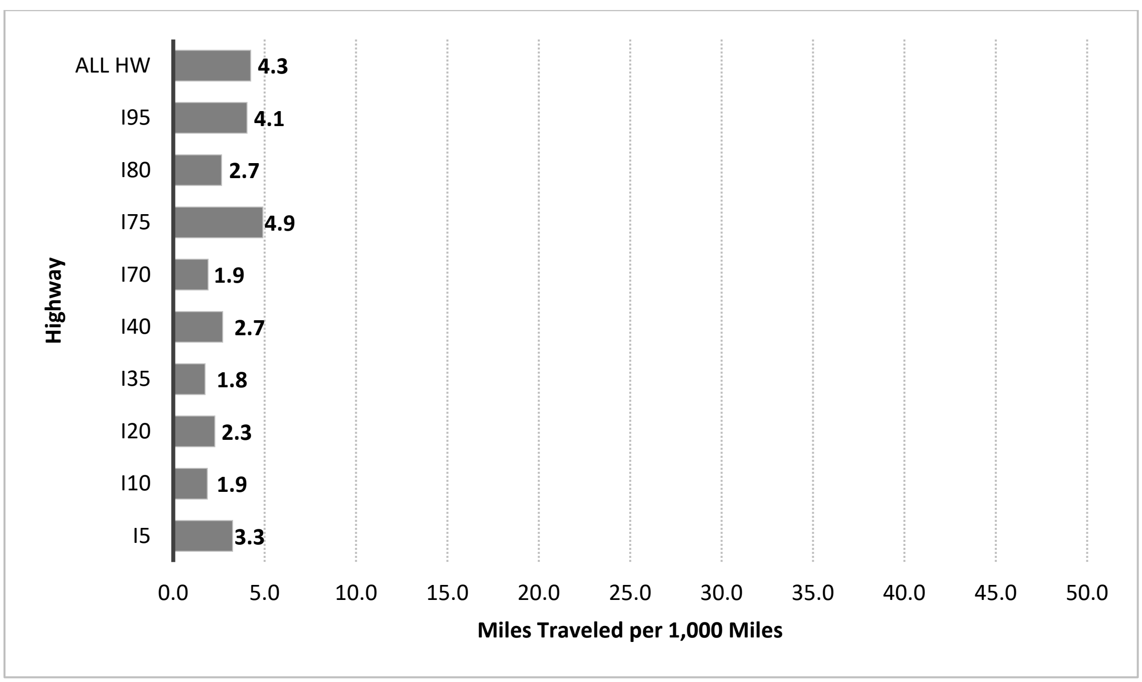

Figure 70. Chart. Highway miles traveled in highway ODDs for lane deviation type 3: 33-45 inches, outside lane (per 1,000 miles traveled).

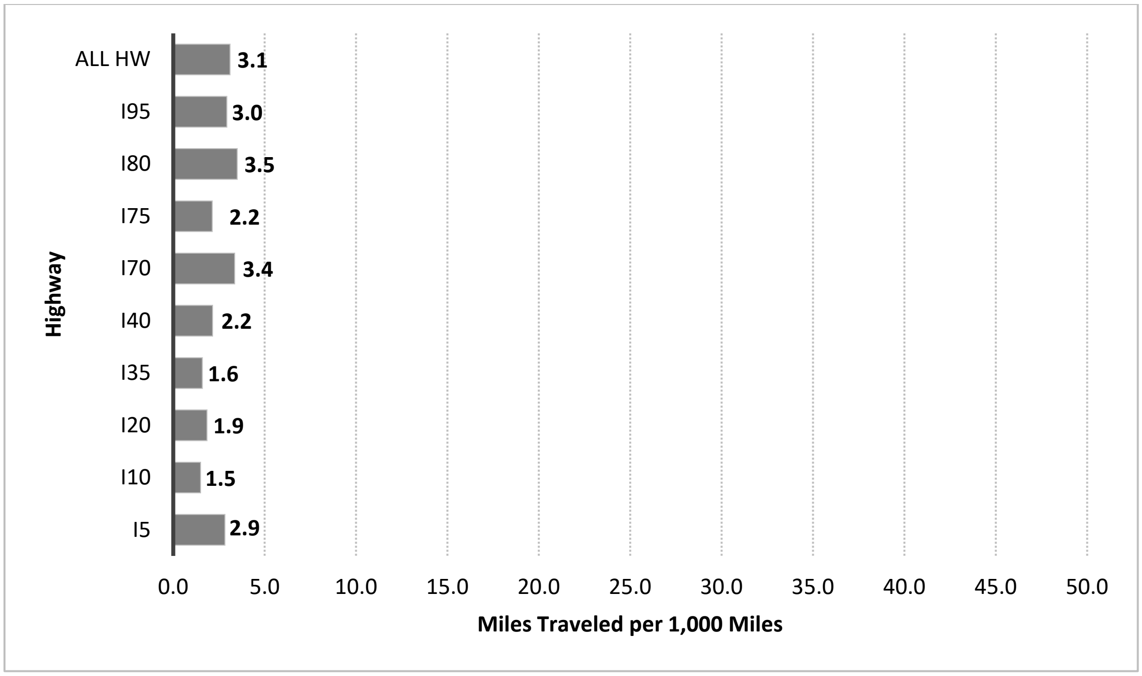

Figure 71. Chart. Highway miles traveled in highway ODDs for lane deviation type 4: greater than 45 inches, outside lane (per 1,000 miles traveled).

Lane Deviation Behavior by Speed Limit ODD

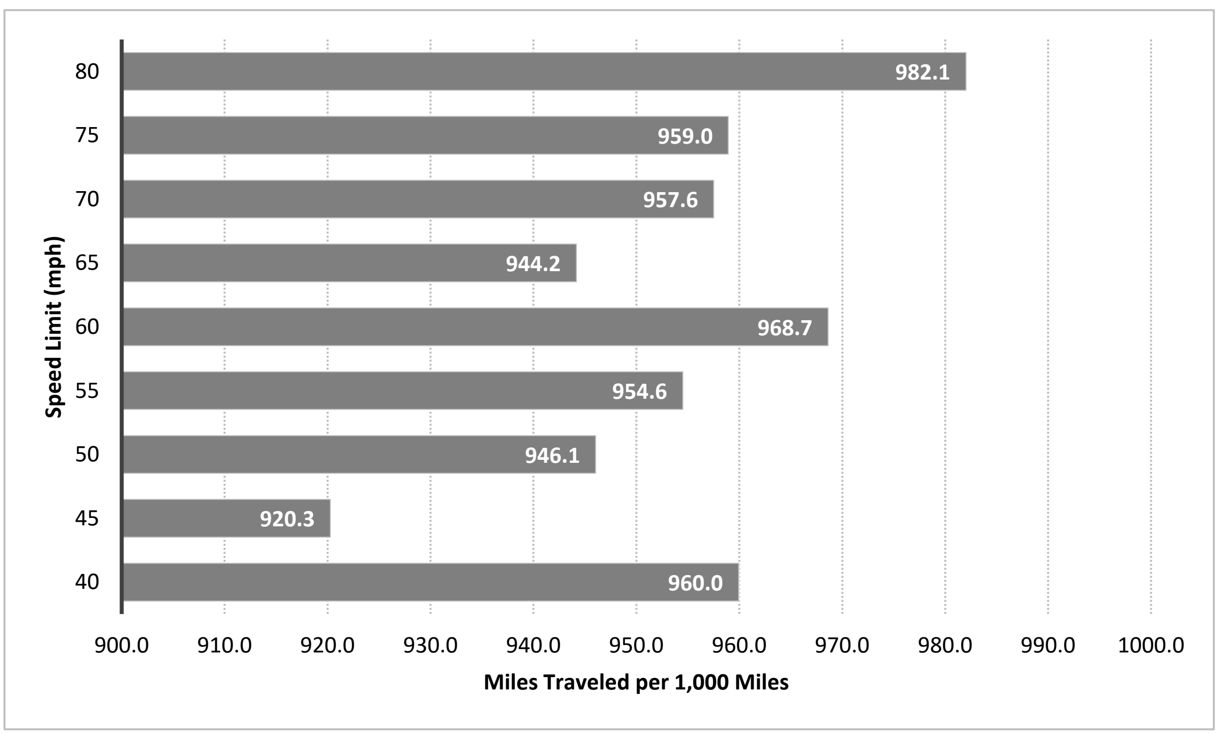

Figure 72. Chart. Highway miles traveled in different speed limit ODDs for lane deviation type 1: 0-21 inches, inside lane (per 1,000 miles traveled).

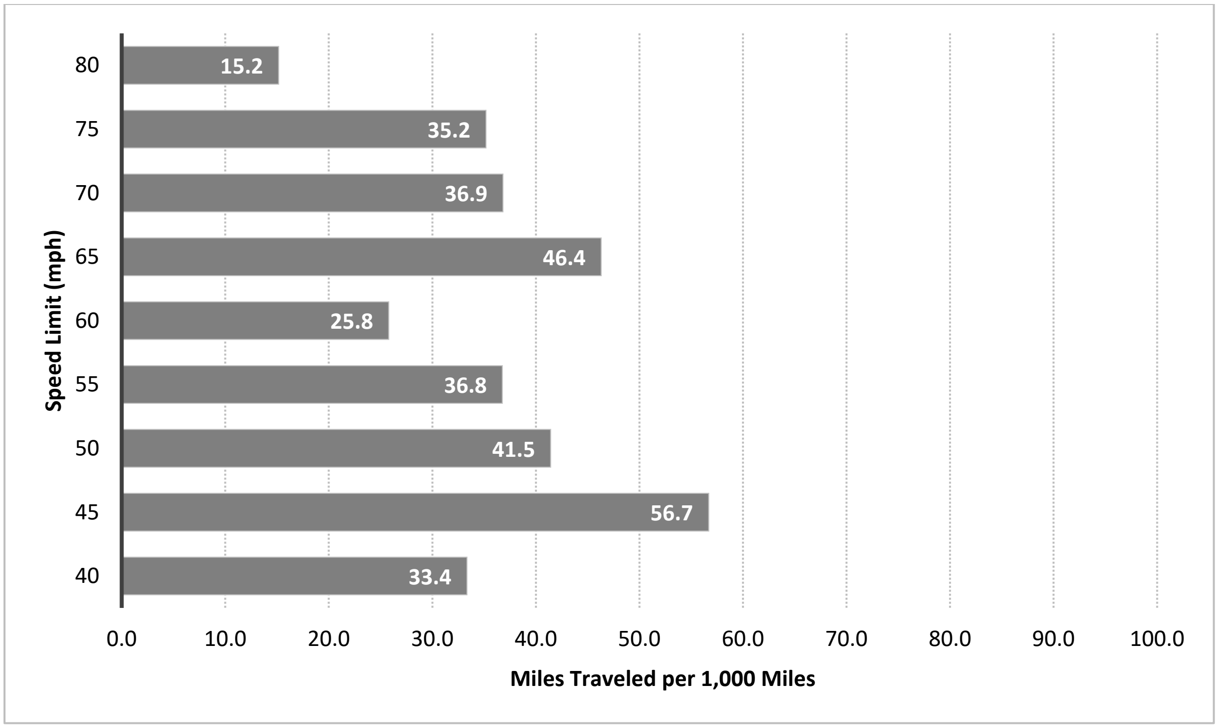

Figure 73. Chart. Highway miles traveled in different speed limit ODDs for lane deviation type 2: 21-33 inches, outside lane (per 1,000 miles traveled).

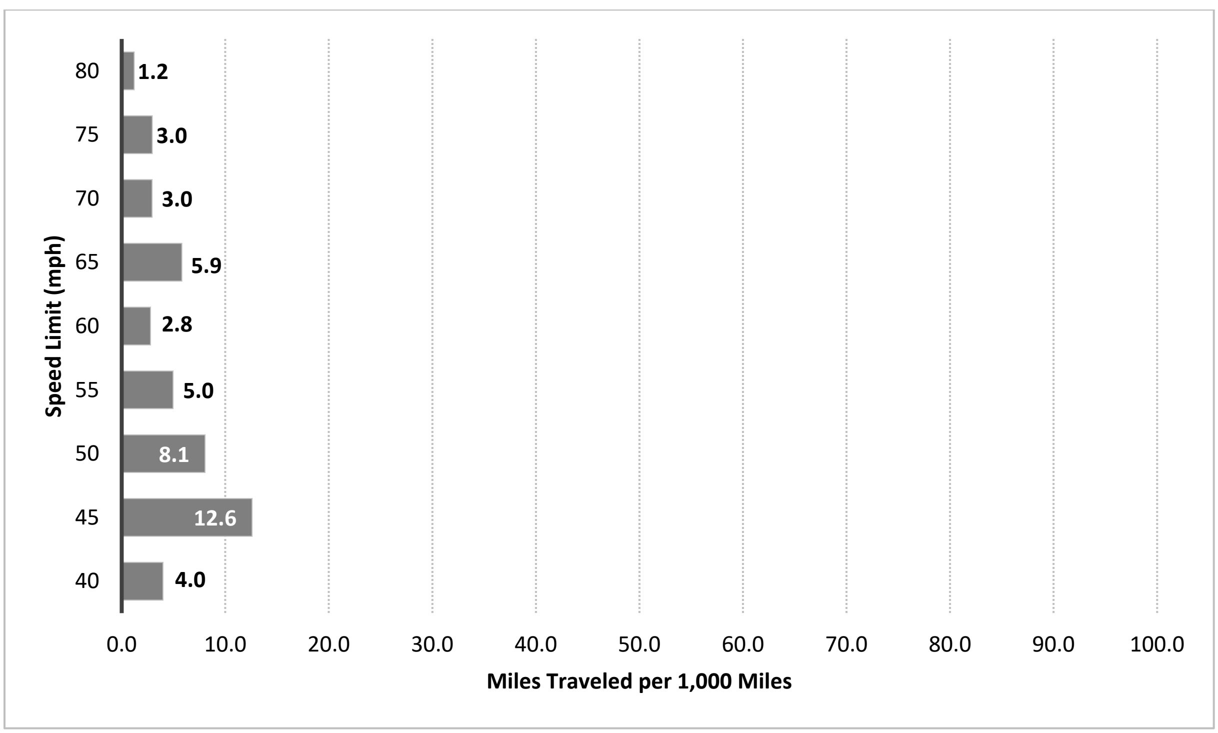

Figure 74. Chart. Highway miles traveled in different speed limit ODDs for lane deviation type 3: 33-45 inches, outside lane (per 1,000 miles traveled).

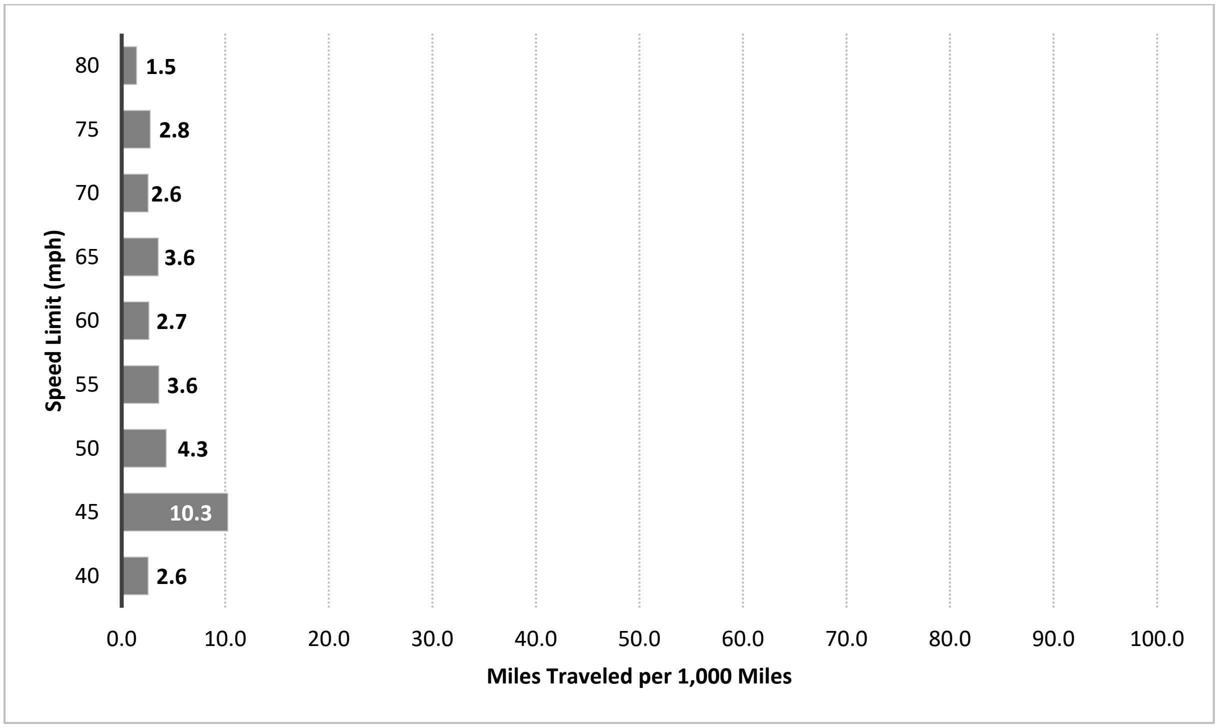

Figure 75. Chart. Highway miles traveled in different speed limit ODDs for lane deviation type 4: greater than 45 inches (per 1,000 miles traveled).

Lane Deviation Behavior by Number of Lanes

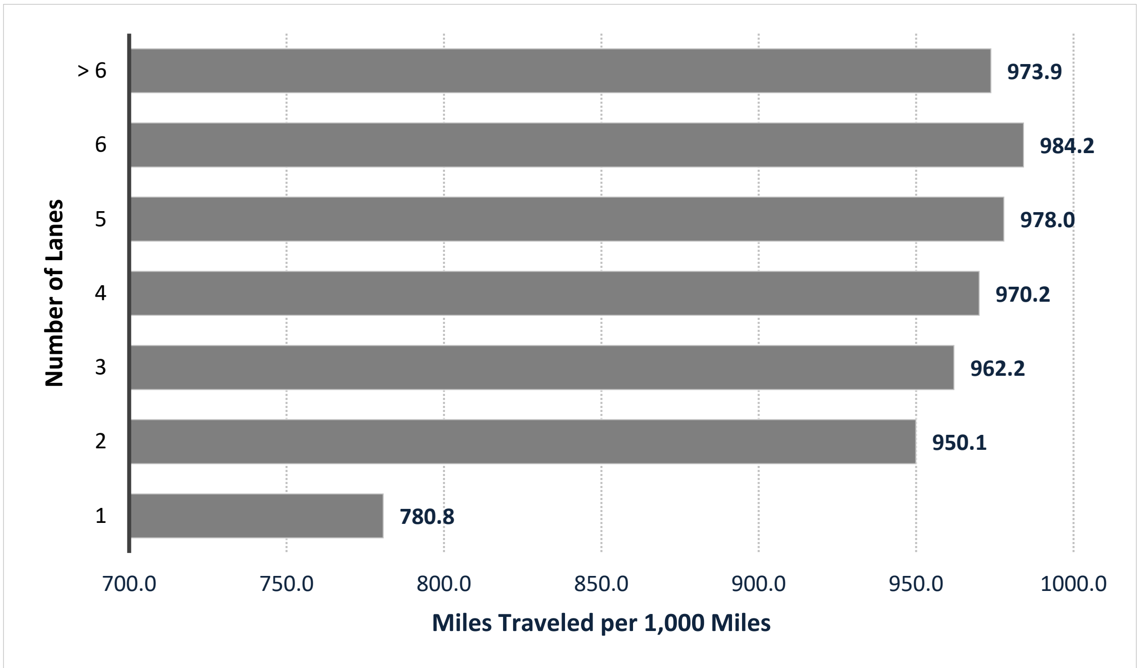

Figure 76. Chart. Highway miles traveled by number of lanes for lane deviation type 1: 0-21 inches, inside lane (per 1,000 miles traveled).

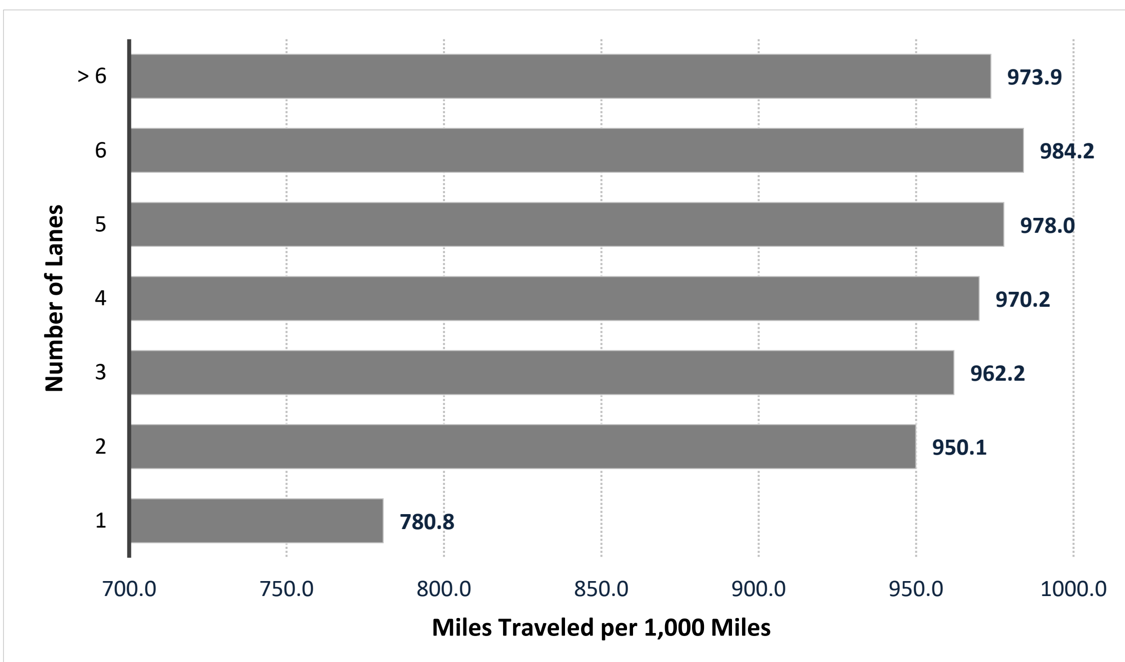

Figure 77. Chart. Highway miles traveled by number of lanes for lane deviation type 2: 21-33 inches, outside lane (per 1,000 miles traveled).

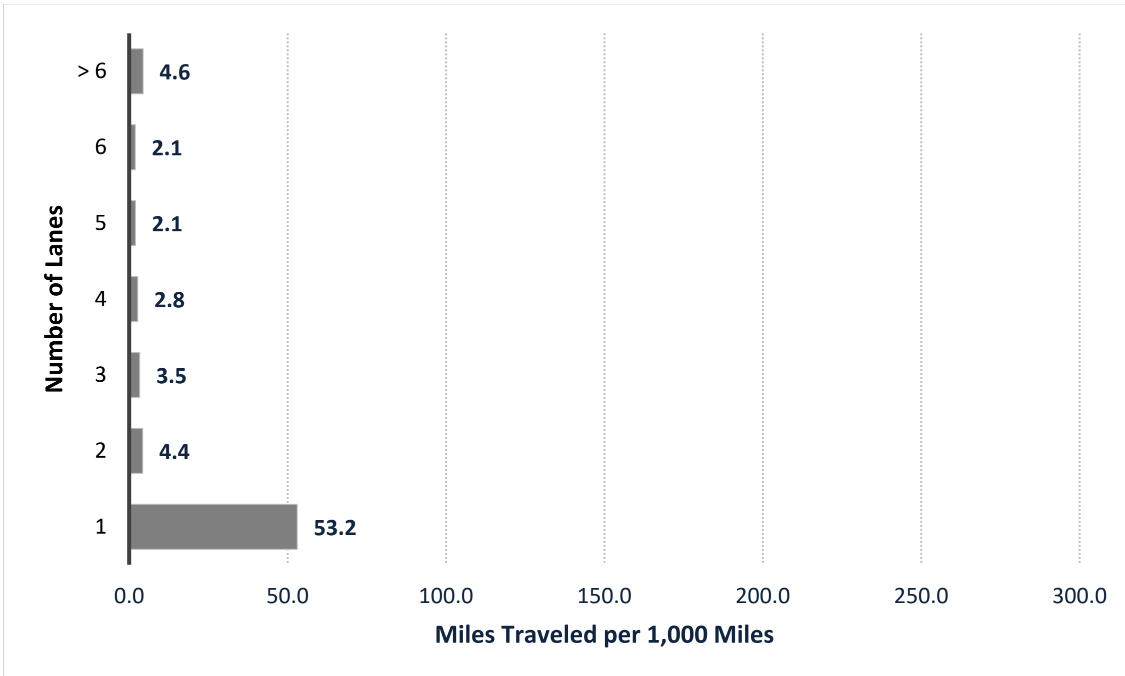

Figure 78. Chart. Highway miles traveled by number of lanes for lane deviation type 3: 33-45 inches, outside lane (per 1,000 miles traveled).

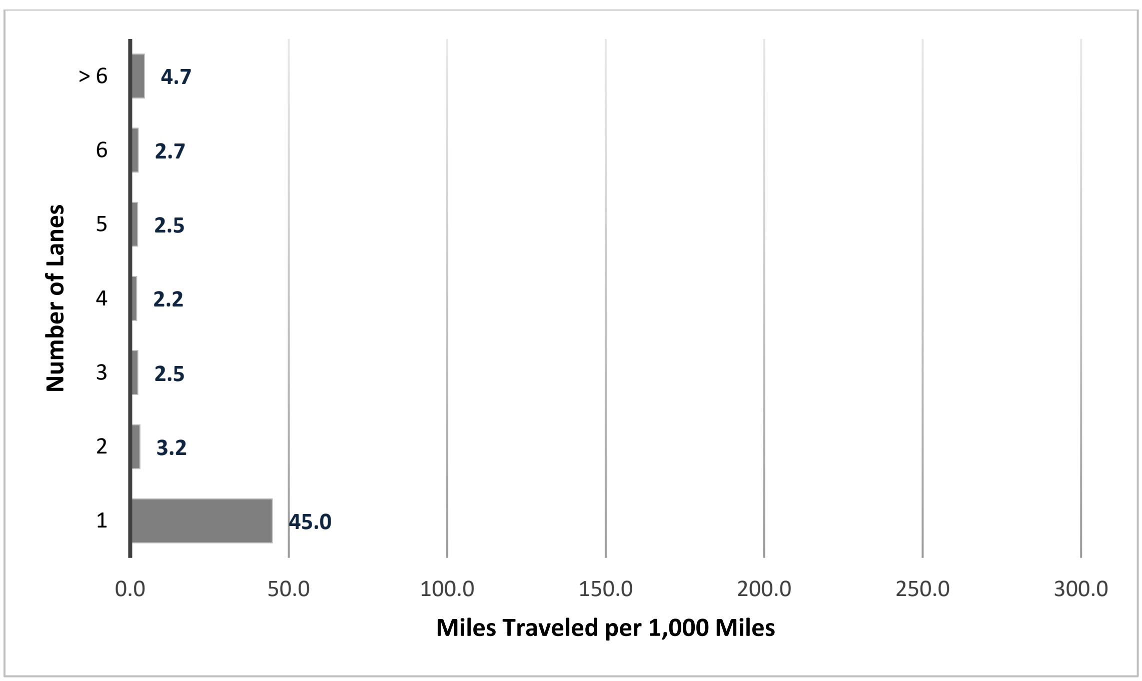

Figure 79. Chart. Highway miles traveled by number of lanes for lane deviation type 4: greater than 45 inches, outside lane (per 1,000 miles traveled).

LANE STABILITY

Lane Stability Behavior by Highway ODD

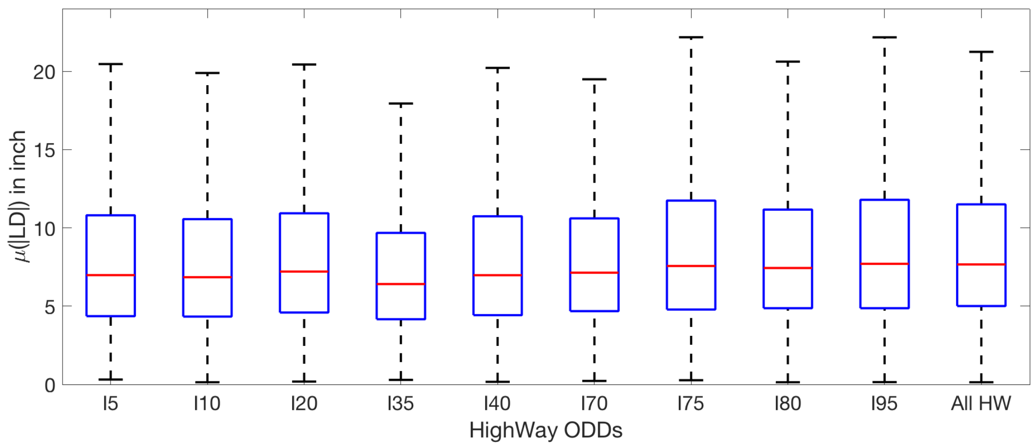

Figure 80. Chart. Lane stability type 1 by the 10 highway ODDs.

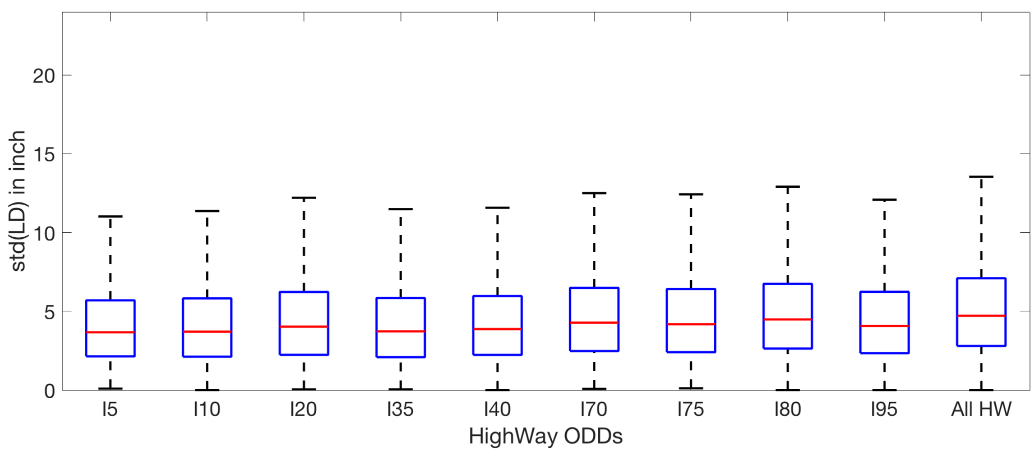

Figure 81. Chart. Lane stability type 2 by the 10 highway ODDs.

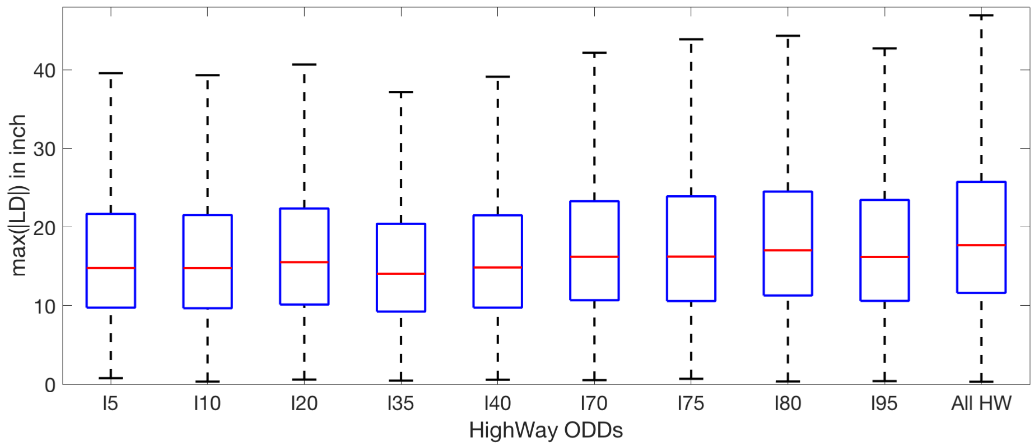

Figure 82. Chart. Lane stability type 3 by the 10 highway ODDs.

Lane Stability Behavior by Speed Limit ODD

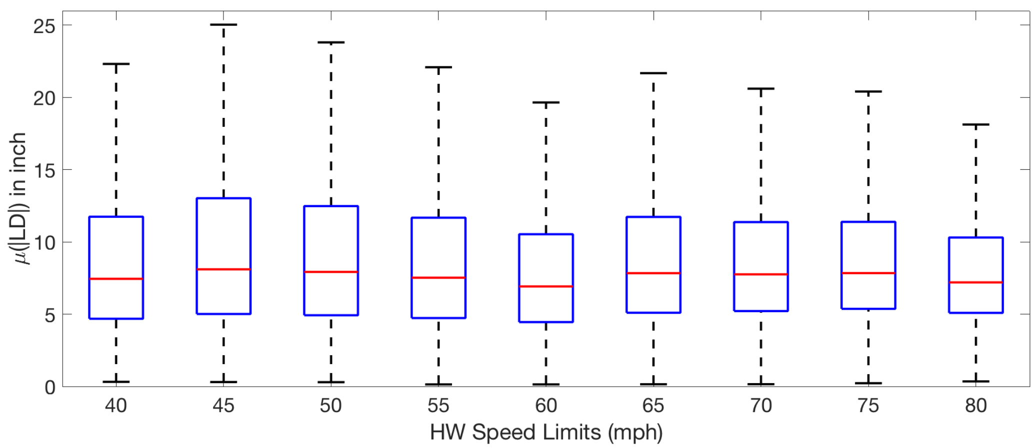

Figure 83. Chart. Lane stability type 1 by speed limit.

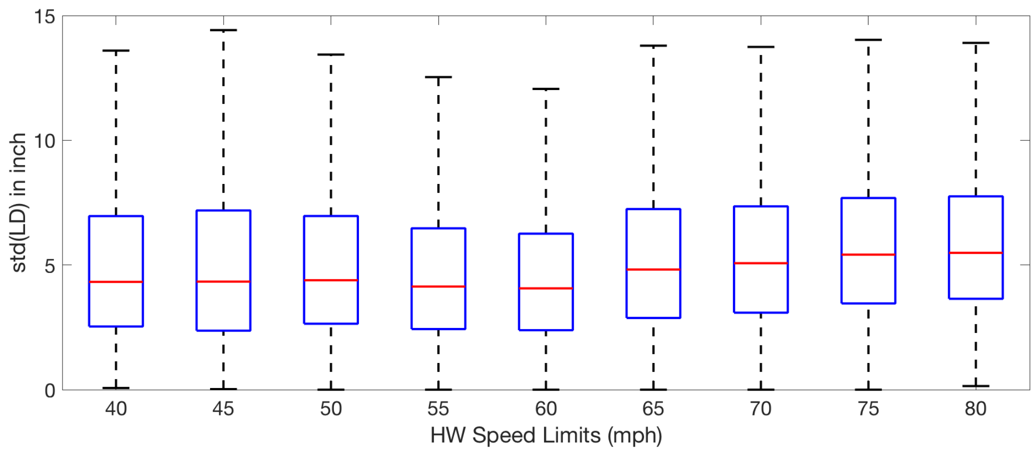

Figure 84. Chart. Lane stability type 2 by speed limit.

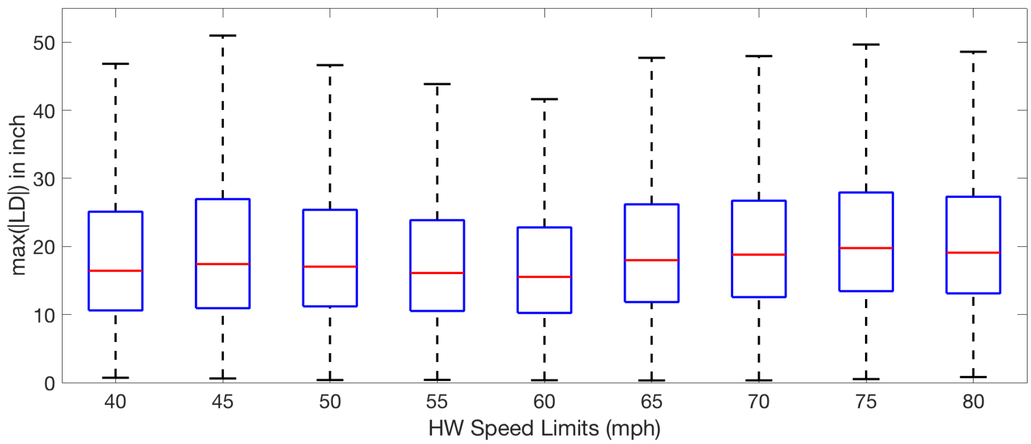

Figure 85. Chart. Lane stability type 3 by speed limit.

Lane Deviation Behavior by Number of Lanes

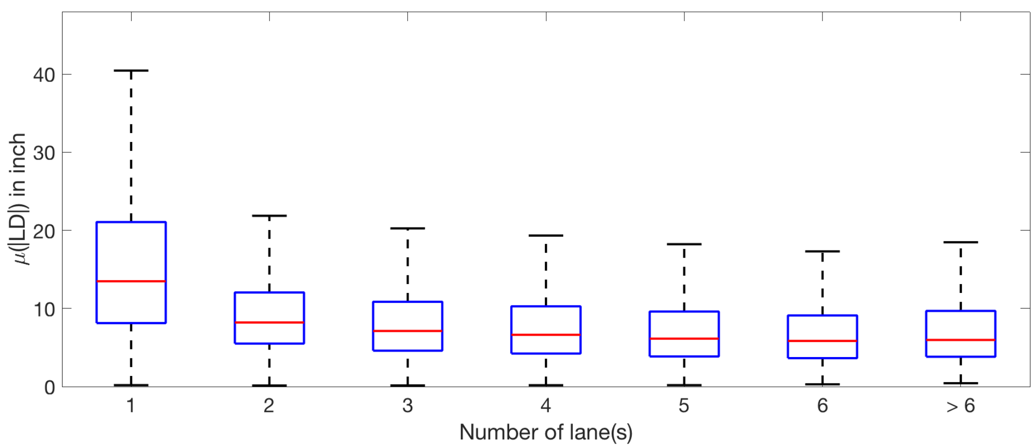

Figure 86. Chart. Lane stability type 1 by number of highway lanes.

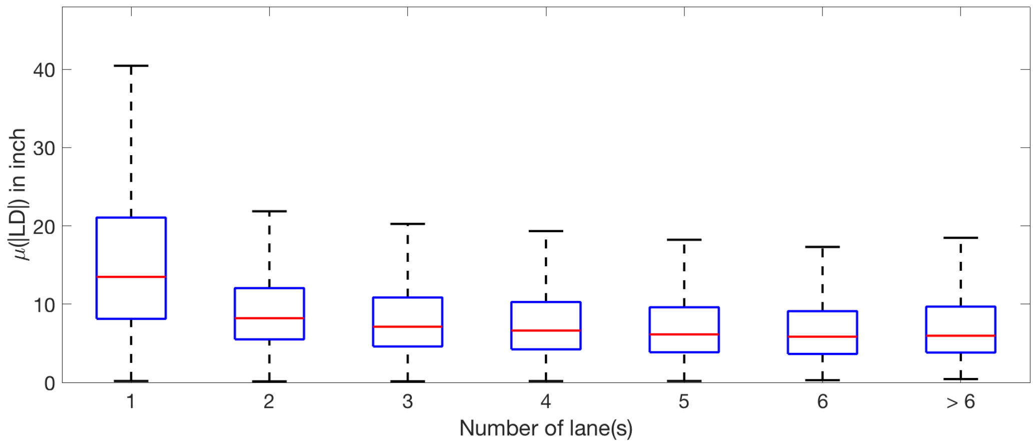

Figure 87. Chart. Lane stability type 1 by number of highway lanes.

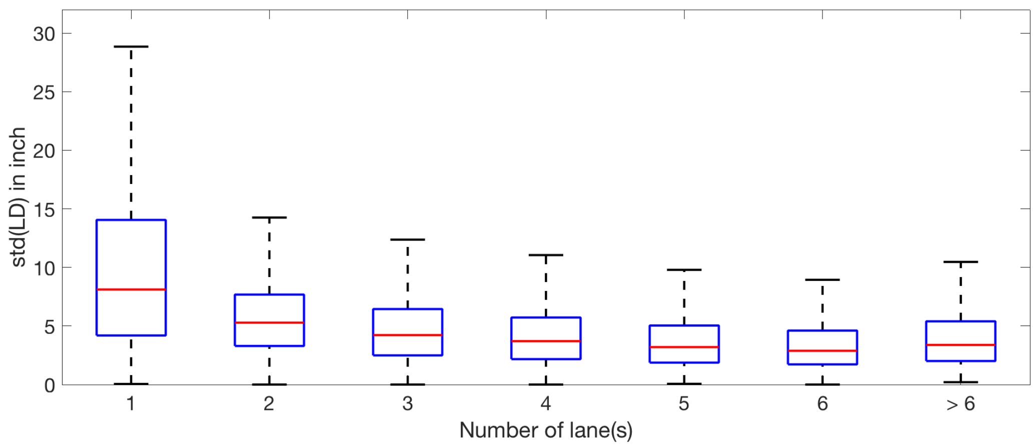

Figure 88. Chart. Lane stability type 2 by number of highway lanes.

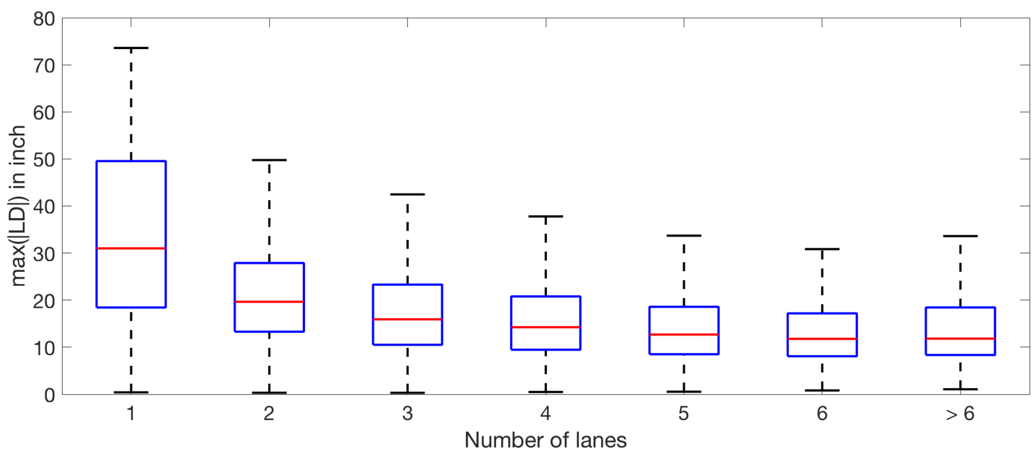

Figure 89. Chart. Lane stability type 3 by number of highway lanes.

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