AN INVESTIGATION INTO VEHICLE ACCELERATION CHARACTERISTICS ON FREEWAY LOOP RAMPS

A Thesis

by

JAYSON MARK STIBBE

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Chair of Committee,	H. Gene Hawkins
Committee Members,	Dominique Lord
	Swaroop Darbha
Head of Department,	Robin Autenrieth

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ABSTRACT

Freeway loop ramps are the most restrictive common interchange ramp design, with sharp curves and low design speeds. Drivers utilizing these ramps can be forced to accelerate rapidly on entry ramps or decelerate rapidly on exit ramps. This thesis has several goals: to gain information about acceleration and deceleration on freeway loop ramps—both where it occurs and the magnitude of the speed change rate; to evaluate what ramp characteristics are most predictive of speed change rate and form models based off of these characteristics; to use the observed speed change rates to form a way to test for the adequacy of auxiliary lanes.

To accomplish these goals, the author uses a large dataset from the Strategic Highway Research Program 2 Naturalistic Driving Study (SHRP2 NDS). The dataset contains time-series vehicle dynamic data from nearly 2,000 vehicle trips on 20 freeway loop ramps in 5 states. The author supplemented this data set to be able to tie the dataset to physical locations and analyze the impact of various ramp characteristics on the speed change rates. The author uses two new terms, deceleration ratio and acceleration ratio to show where on the loop ramps deceleration and acceleration occur. Next, the actual deceleration rates and acceleration rates are shown and compared to the commonly used current rates. The author then models these rates using the most predictive ramp variables—radius of curve and speed limit of the adjacent freeway. Next, the author calls for updating the assumption of vehicle acceleration on ramps, suggesting that the rates of acceleration and deceleration may be closer than previously assumed and that

acceleration may not be constant on loop ramps. Finally, the author introduces a method for determining the adequacy of auxiliary lanes on freeway loop ramps.

In this thesis, the author finds that much of the acceleration on entrance loop ramps and deceleration on exit loop ramps occurs outside of the loop ramp proper—on either the freeway or the auxiliary lanes—and notes the importance of adequate auxiliary lanes. The author finds that deceleration rates on exit loop ramps may be lower than previously thought and recommends that a lower rate be used for design purposes. The author finds that using the “normal” acceleration rate of 3.6 ft/sec^2, many of the studied ramps do not provide adequate room for vehicles to reach the freeway speed limit before they are forced to merge onto the freeway.

DEDICATION

To Lexi, John, Juli, and everyone else who goes out of their way to do the little things.

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Some of the data collected in Chapter III was collected either by or under the supervision of Marcus Brewer of the Texas A&M Transportation Institute.

All other work conducted or the thesis was completed by the student independently.

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CHAPTER I

INTRODUCTION

Freeway loop ramps have the lowest design speeds among common interchange ramps. The low design speeds require drivers to change speed more rapidly. Because of the larger difference in design speeds between the higher-speed freeway and the loop ramps, drivers must accelerate and decelerate more in transition to or from these ramps than on other ramp types. Fitzpatrick (*1*, *2*) realized the need to better understand the nature of speed-changing behavior on ramps, as drivers can change speed in a number of places: on the ramp proper, the auxiliary lanes, and the freeway itself. A recent report has concluded that on loop ramps, drivers do change speed on both the auxiliary lanes and on the ramp proper (*3*).

Many studies have attempted to model the role of geometric characteristics on operating speed of freeway loop ramps. Such studies have predicted operating speed from the radius of curve, the length of the auxiliary lane, the lane width, and other geometric variables. Other studies have been conducted to determine the acceleration or deceleration of vehicles in auxiliary lanes. Less research has been conducted that examines the rate of acceleration on the ramp proper. Data available from the State Highway Research Program 2 Naturalistic Driving Study (SHRP2 NDS) provides a unique opportunity to obtain hundreds of unique vehicle profiles on several loop ramps located in six different states. A more thorough understanding of how geometric characteristics impact acceleration and deceleration behavior could lead to improvements in safety or input in loop ramp design.

Problem Statement

Freeway loop ramps are the most restrictive common interchange ramp design, with sharp curves and low design speeds. Drivers utilizing these ramps can be forced to accelerate rapidly on entry ramps or decelerate rapidly on exit ramps. As bottlenecks, freeway ramps are critical to the operations of freeways. Research that shows the impact of loop ramp design elements on vehicle dynamics would aid in the understanding of these critical roadway segments. Additionally, information on the existing acceleration and deceleration rates on loop ramps could be used to update the acceleration rate assumptions and give insight into the necessary length of auxiliary lanes.

Research Objectives

The main goal of this thesis is to study vehicle acceleration and deceleration on loop ramps and to determine the impact of various design elements. This study will use data from the SHRP2 NDS to measure the acceleration of hundreds of vehicles on freeway loop ramps in the six states participating the SHRP2 study. The objectives of this research are as follows:

- Utilize the SHRP2 NDS to obtain meaningful data that can be used to determine driver speed change rate on loop ramps.

- Find where on freeway loop ramps most vehicles accelerate and decelerate.
- Measure the impact of various geometric design elements on the acceleration and deceleration of vehicles on freeway loop ramps.
- Determine what variables are most impactful to the rate of speed change on the ramp proper of a freeway loop ramp.
- Evaluate the observed speed change rates to determine whether they are appropriate for freeway loop ramp facilities.
- Model the speed change rate for vehicles on loop ramp facilities based on the most impactful geometric variables.

CHAPTER II

LITERATURE REVIEW

Loop Ramps

Ramps are often considered to be critical sections of a freeway. They provide all entering and exiting opportunities for vehicles on the freeway (*4*). The freeway sections immediately surrounding ramps are often bottlenecks on a freeway facility due to the higher friction experienced (*5*). Although effort should be taken to reduce the friction and negative operational impacts of ramps, there are other important considerations to account for when designing a ramp. Torbic et al. (*3*) note that projects involving interchange ramps are often the most complex and expensive projects. Agencies making costly decisions on interchanges must therefore weigh many interacting factors, such as safety, cost, operations, and the impact on the surrounding area. Although loop ramps typically have the slowest design speeds of interchange ramps, they are still commonly employed at interchanges in anywhere from one to four quadrants. Additionally, loop ramps can provide operational benefits over conventional diamond interchanges by allowing free-flowing left turn movements. Because of the frequency with which these ramps are used, it is important to know about their impact on road users. Figure 1 is reprinted from Torbic et al. (*3*) and provides many of the interchange configurations where loop ramps are implemented.

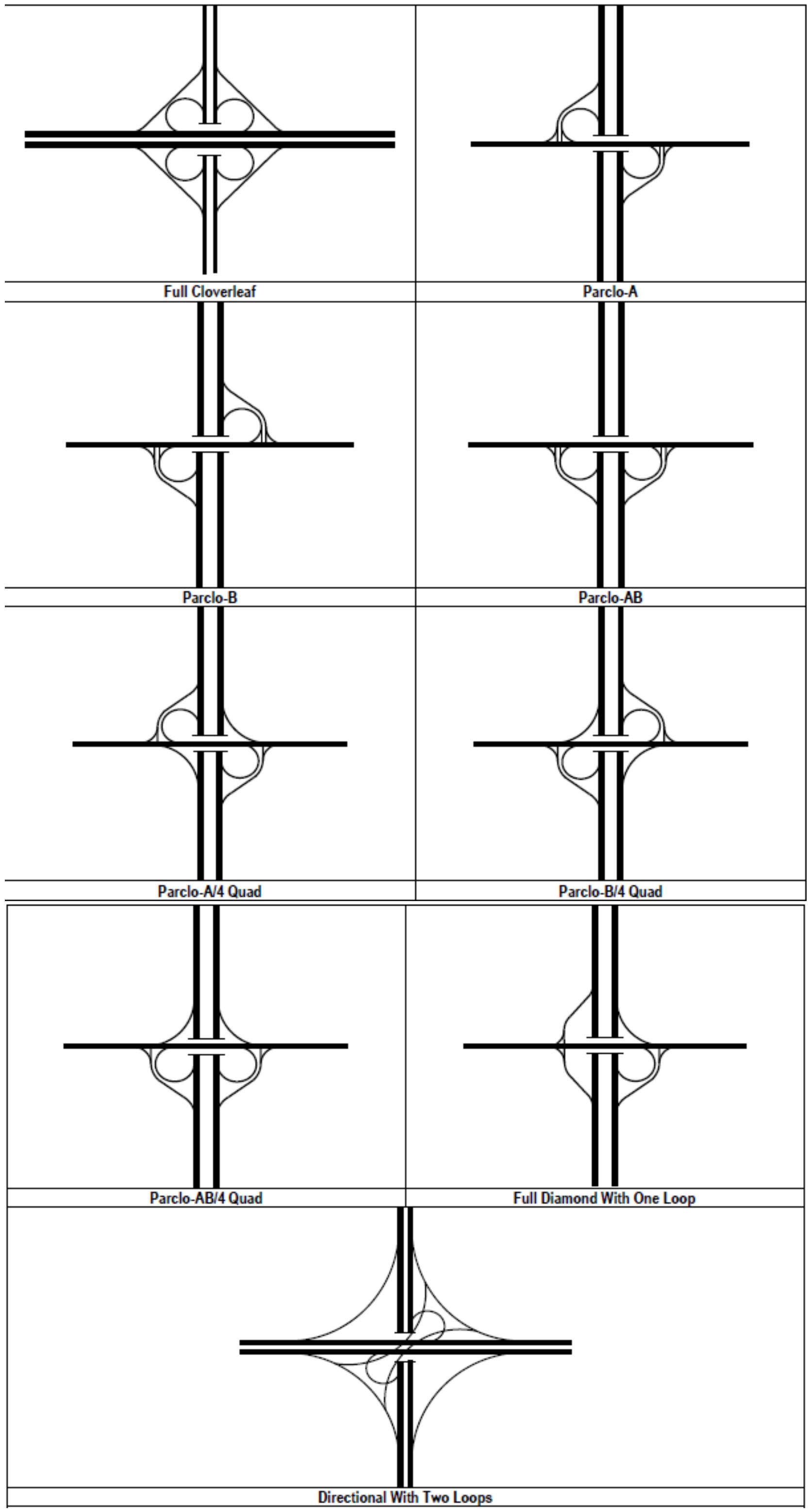


Figure 1. Interchange configurations with loop ramps. Reprinted from Torbic et al. (*3*).

Current Design Practices

Torbic et al (*3*) recently reviewed the current design guidelines for loop ramps by focusing on the design criteria for sharp horizontal alignment. The foremost resource they reviewed was AASHTO's Green Book (*6*). Although Chapter 10 of the Green Book, Grade Separations and Interchanges, contains some pertinent information about the design of loop ramps, one must look at other sections to get a complete idea of their recommended design guidelines (*7*). Chapters 3 and 4 provide the reader with many of the design elements to consider when designing horizontal curves. These include the following:

- Minimum radius,
- Sight distance,
- Superelevation,
- Side friction factor,
- Distribution of superelevation and side friction,
- Effect of grades, and
- Lane and shoulder width.

When designing a horizontal curve, the goal should be to balance the forces acting on the vehicle as much as practical to provide vehicle stability. The centripetal acceleration experienced by a vehicle on a curve must be balanced by some combination of superelevation and side friction, as shown by Equation 1, known as the basic curve formula (*6*). This design speed is used as an overall design control when establishing other roadway elements, such as the radius of curve and the superelevation.

$$0.01e + f = \frac{V^2}{15R} \tag{1}$$

Where: e = superelevation, percent;

f = side friction factor, decimal;

V = vehicle speed, mph;

R = radius of curve, feet; and

g = the gravitational constant, 32.2 ft/s^2.

In addition to these important design elements, the Green Book (*7*) also notes other important design controls when designing a horizontal curve. Many of these controls are established with the idea of providing positive guidance for drivers and/or enhancing safety. For example, it states that curves should have a minimum length, dependent upon the total deflection angle of the curve. Likewise, it states that certain types of curves, such as broken-back curves, should be avoided unless absolutely necessary.

In Chapter 10 of the Green Book, a list of four-leg interchange designs is given (*7*). Three of these interchange designs include loop ramps: ramps in one quadrant, directional and semidirectional interchanges, and full or partial cloverleafs. Ramps in one quadrant do not necessarily involve loop ramps, are rarer than other interchange designs, and are generally used in low-volume settings where they are topographically appropriate. On the other hand, directional and semidirectional interchanges are typically used in urban areas or in areas of high-volume. These interchange designs use some combination of directional, semidirectional, and loop ramps to fit the topography and demand conditions while minimizing impact to the area and minimizing the amount of weaving necessary (*7*). Cloverleafs are the most common source of loop ramps, with many possible arrangements (as shown in Figure 1). Loop ramps require more space than other types of ramps. They require rapidly increasing sizes of land as the design speed of the ramp rises. Despite requiring more land, loop ramps can be a cost-minimizing option due to the simple design and fewer structures. Increasing the design speed of the ramp leads to increasing the radius of the ramp, which also increases the travel distance for the driver. This tradeoff is important when selecting the design speed for a loop ramp.

Safety on Loop Ramps

The loop ramp design often involves weaving maneuvers on the freeway, particularly when collector-distributor roads are not employed (*7*). When space is limited, interchange designs will often use loops with tight curvature. Yates (*8*) found that as the curvature rate increases in loop ramps, so does the accident rate in urban settings. Yates found that the safety of a loop ramp depended upon its location, with the reverse being true for rural areas. This unique finding was reaffirmed by Twomey et al. (*9*) in 1993. These researchers also note that cloverleaf ramps (among other types) should be generally avoided for safety reasons, particularly in high-volume areas where no collector-distributor roadway is implemented. The Green Book notes that acceleration and deceleration lanes are one possible alternative to collector-distributor roadways for safety mitigation on loop ramps (*7*).

Vehicle Dynamics

When a vehicle is going from a high-speed facility to a low speed facility or vice versa, the vehicle must change its speed. Recently, Fitzpatrick et al (*1*) found that "the need to update the speed assumption for the highway and the ramp curve is clear, even though determining the appropriate deceleration rates is difficult." It is important that the manner in which vehicles accelerate or decelerate is understood so that facilities can be designed to be as safe and effective as possible.

Acceleration and Deceleration Rates

The ability of a vehicle to accelerate or decelerate depends on the vehicle's performance (*10*). The Traffic Engineering Handbook (*10*) gives information on typical acceleration and deceleration rates. A vehicle has a maximum acceleration rate and a normal acceleration rate; it has a maximum deceleration rate and a normal deceleration rate. Additionally, vehicles can decelerate without applying brakes due to the forces resisting the motion of the vehicle, such as the force of friction. The maximum acceleration rate is dependent upon the vehicle's weight and horsepower but is around 8 ft/s^2 for passenger cars. The normal acceleration rate, however, is less than half of that, at approximately 3.6 ft/s^2. As these values are reasonably old, it is possible that as the performance of newer cars increases, these acceleration rates will increase. The Green Book (*7*) uses lower performance vehicles for design applications as these vehicles will have dampened acceleration and deceleration values. They also note that the initial speed of the vehicle has an effect on vehicle acceleration, as acceleration lessens as the vehicle speed increases.

In NCHRP Report 400, Fambro et al. (*11*) recommend 11.2 ft/s^2 as the threshold for comfortable deceleration and 14.8 ft/s^2 as the deceleration at which most drivers select when stopping for unexpected objects. The deceleration rate commonly used for stopping sight distance calculations is 11.2 ft/s^2 and assumes passenger cars. However, the maximum deceleration rate—an undesirable state of braking typical of emergency stops occurring when wheels are locked—is higher than this and largely dependent on the available tire friction. For example, motorcycles or passenger cars with an available tire-friction coefficient of 0.6 can decelerate at approximately 19.3 ft/s^2. On the other hand, large trucks have lower coefficients of friction leading to less rapid deceleration and longer stopping distances. Normal, or comfortable deceleration rates are thought to be up to 10 ft/s^2 (*10*). These rates have different applications for different scenarios.

Auxiliary Lanes

The Green Book defines auxiliary lanes as "the portion of the roadway adjoining the traveled way for speed change, turning, storage, for turning, weaving, truck climbing, and other purposes supplementary to through-traffic movement (*7*)." An example of an auxiliary lane is provided in Figure 2. On freeways, auxiliary lanes are often used to accommodate speed changes. There has been substantial effort taken to determine when auxiliary lanes should be used, as well as what length to use to accommodate the desired speed change. The auxiliary lane can be classified as either an acceleration lane or a deceleration lane for vehicles entering or exiting a higher-speed roadway, respectively. In 2012, Fitzpatrick et al. (*1*) developed a procedure to calculate the necessary length of a deceleration lane but admitted that some of the assumptions they made for the procedure should be questioned, as they used information that could require updating provided in the 1965 *Blue Book.* The Green Book calculates the necessary length of auxiliary lanes by considering the distance required to change speed from one speed to the next.

Our knowledge is similarly limited on the proper length of acceleration lanes. Fitzpatrick and Zimmerman (*2*) suggested that a constant acceleration rate of 2.5 ft/s^2 be used to determine the length of acceleration lanes, noting that using this value would result in acceleration lane lengths longer than those recommended by the 2004 Green Book. However, Yang et al. (*12*) found in 2017 that using a constant acceleration rate would not be appropriate for determining the necessary length of an acceleration lane. Instead, Yang et al. developed a piecewise-constant acceleration model, where the acceleration was considered constant over smaller intervals.

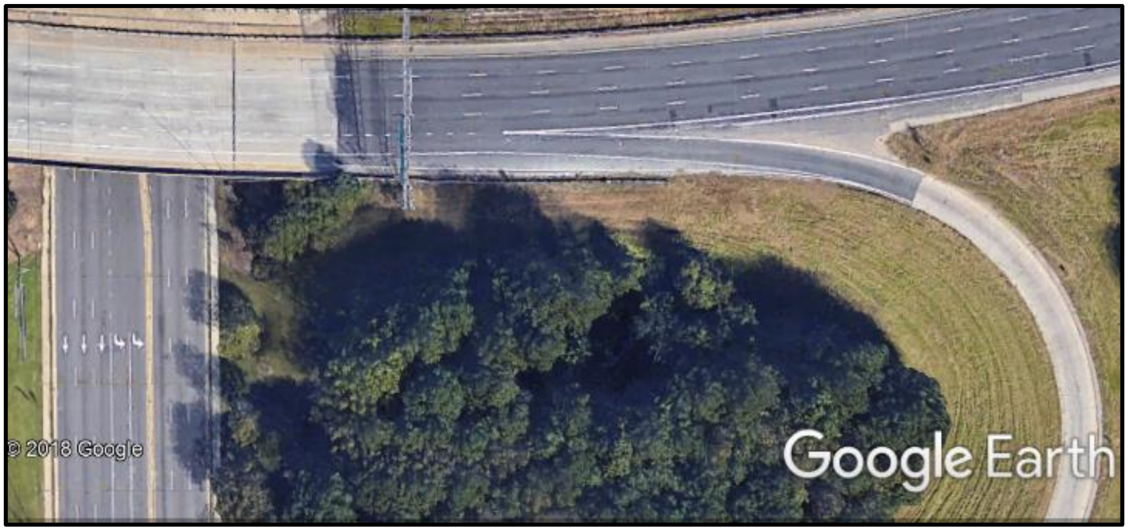


Figure 2. Example of a Freeway Deceleration Lane.

Importantly, Torbic et al. (*3*) found that not all of the vehicle's acceleration or deceleration occurs within the auxiliary lane, but that the vehicle changes speed along the ramp proper as well. Additionally, drivers likely begin decelerating before reaching the auxiliary lane when exiting a freeway and continue accelerating after leaving the auxiliary lane when entering a freeway (*1*). Because acceleration and deceleration related to ramps can occur on the ramp proper, the auxiliary lanes, and the freeway itself, the behavior can be quite complex.

Factors Impacting Ramp Speed

Intuitively, the acceleration or deceleration of a vehicle on ramp is related to the vehicle's operating speed and particularly the vehicle's change in operating speed between segments. There have been many models constructed that aim to relate the operating speed of a vehicle with a geometric feature of the ramp. Typically, models predicting speed only use one or two factors, as there are often unknown levels of correlation found between geometric elements (*13*). Some of the factors used in ramp speed-prediction models are provided below:

- Radius of curve (*3,14,15,16,17*)
- Superelevation (*13,18*)
- Curvature change rate (*13,18*)
- Type of speed change lane (*3*)
- Lane width (*3*)
- Shoulder width (*3*)
- Length of auxiliary lane (*15*)
- Type of curve radius (simple or compound) (*3*)
- Lane position in ramp (outside or inside) (*3*)
- Vertical grade (*16*)
- Length of horizontal curve (*17*)
- Distance to downstream intersection (for exit ramps) (*14*)
- Angle of convergence (for entrance ramps) (*19*)

On this list, only the models constructed by Torbic et al. (*3*) were made exclusively for loop ramps. The other models were made to be generalized to different ramp types. Clearly, many components of geometric design could factor into vehicle dynamics along a ramp.

It is worth noting that several of the factors listed are related to the selection of the design vehicle for the ramp. Interchange ramp design, auxiliary lane design, lane width and superelevation can all be affected by the selection of the design vehicle (*20*).

Data Collection

Historically, when collecting data on vehicle acceleration and deceleration, researchers have collected vehicle speed intermittently and used that information to calculate the acceleration rate. In general, the vehicles would travel known distances, with the time differences calculated from video recording and used to estimate the acceleration rate (*4*,*21*).

Advantages of SHRP2 NDS over Traditional Data Collection Methods

A recent study, known as the SHRP2 Naturalistic Driving Study has shown itself to be a tremendous resource for analyzing detailed data on the dynamics of vehicles in the six participating states. In each vehicle, a data acquisition system (DAS) was installed to collect data from four video cameras attached to the car, accelerometers, vehicle network information, a GPS system, and other sensors (*22*). During operation, the DAS recorded data every tenth of a second on many variables, including velocity, 3-axis acceleration, GPS data, and vehicle network data, while subsequently recording multiple videos and maintaining other sensor information. This abundance of data is a tremendous resource for those interested in analyzing the dynamics of vehicles participating in study. As researchers were not required to be physically present at study sites while this data was collected, those using this data can obtain a sample that is bigger and more diverse than they could otherwise. Using the SHRP2 NDS dataset, researchers are able to analyze magnitudes more data than they would otherwise.

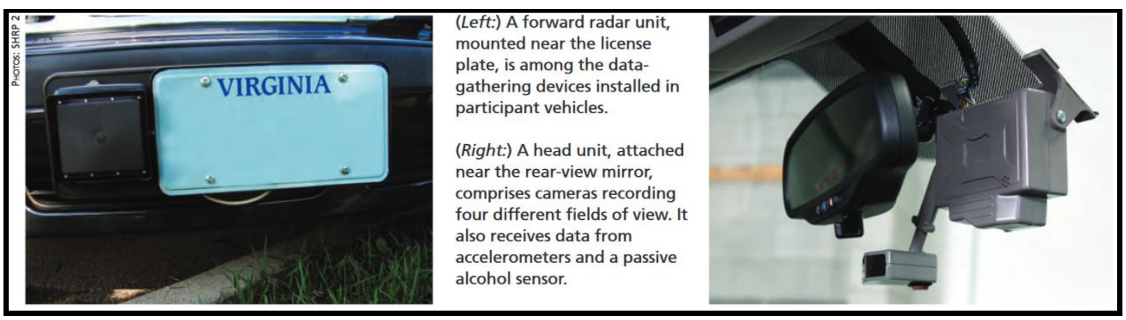
By having a detailed dataset and a participant pool of more than 3,000 drivers across the country, the SHRP2 NDS provides an unprecedented opportunity to investigate relationships between roadway conditions and driver behavior. The complete NDS dataset contains more than 3,500 driver-years of naturalistic driving data, compiled from more than 5 million trips (*22*) and occurring on all types of roadways. With the sheer volume of vehicle miles traveled spread over many participants, the typical limitations on previous instrumented vehicle studies (e.g., number of sites, number of drivers, number of vehicles) do not apply to this study. Moreover, the study maintains the benefits (e.g., level of detail, continuous recording, etc.) of the instrumented vehicle method while also taking video recording.

Details of SHRP2 NDS Dataset

The Naturalistic Driving Study, conducted as part of SHRP2, was designed to address the role of driver performance and behavior in traffic safety and to better understand the interaction between the driver and the driving environment, particularly during crashes or near-crashes (22). By recording many aspects of the driving environment, changes in collision risk could be better understood. Study participants were recruited from six cites in six different states. Vehicles were outfitted with instrumentation in these states as follows:

- Bloomington, Indiana: 150 vehicles;
- State College, Pennsylvania: 150 vehicles;
- Tampa Bay, Florida: 441 vehicles;
- Buffalo, New York: 441 vehicles;
- Durham, North Carolina: 300 vehicles; and
- Seattle, Washington: 409 vehicles.

Study participants were tested through a variety of personal assessments (e.g., visual, cognitive, and physical capabilities; medical condition; driving knowledge) before being accepted into the program. In many cases, the instrumented cars were driven by multiple participants. Examples and schematics of some of the sensor installations are shown in Figure 3 and Figure 4, reprinted from Campbell (*22*).



(*Left:*) A forward radar unit, mounted near the license plate, is among the data-gathering devices installed in participant vehicles.

(*Right:*) A head unit, attached near the rear-view mirror, comprises cameras recording four different fields of view. It also receives data from accelerometers and a passive alcohol sensor.

Figure 3. Radar and camera units used in the SHRP2 Naturalistic Driving Study. Reprinted from Campbell (*22*).

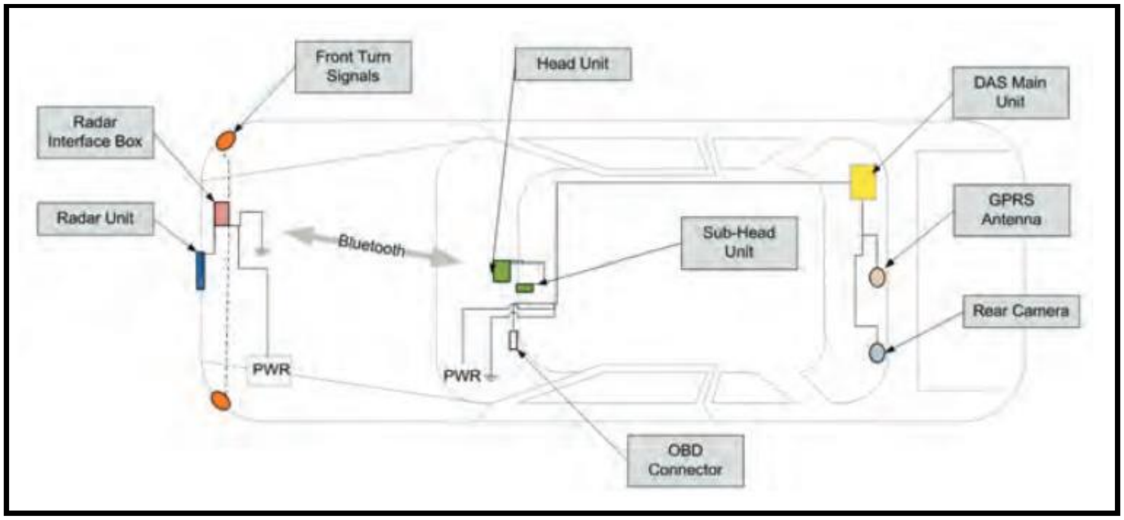


Figure 4. Schematic view of data acquisition system used in SHRP2 NDS. Reprinted from Campbell (*22*).

The DAS continuously recorded data whenever the participant's vehicle was in operation, enabling an exposure-based approach that documented conditions prior to crash events and other incidents. The central computer, or main unit, encrypted and recorded all data on a removable hard drive that was replaced every four to six months. The camera units shown in Figure 3 recorded images in many directions: the forward view from the front windshield; the view of the driver; the view of the left, right, and rear side of the vehicle; and the view of the vehicle's instrument panel, as illustrated in Figure 5, reprinted from Campbell (*22*). A fifth camera took still images of the vehicle's interior at intervals of a few seconds, to document passengers in the vehicle (*22*). The end result of the data acquisition process was an in-vehicle system that continuously records several dozen channels of data, summarized in Table 1, modified from Campbell (*22*).

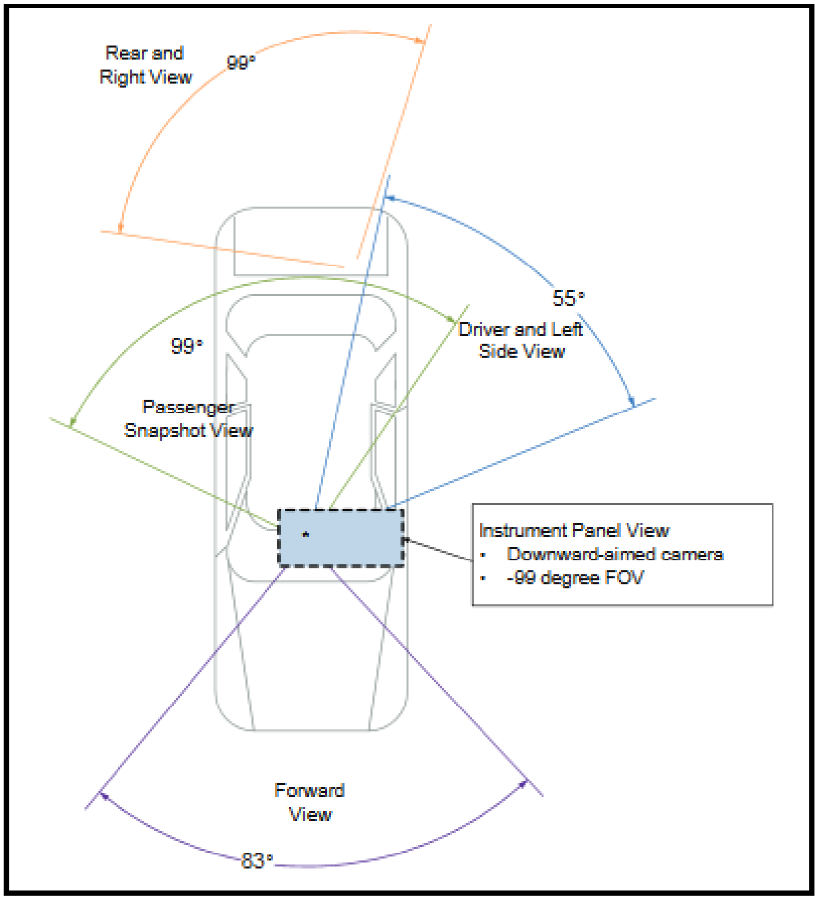


Figure 5. Fields of view for the data acquisition system used in SHRP2 NDS. Reprinted from Campbell (*22*).

The SHRP2 NDS dataset is a source of "big data" that provides an unprecedented resource to analyze detailed data for a large sample of drivers and ramps, offering a basis to critically review and potentially improve current design speed guidance. With more than 3,000 drivers and many thousands of trips recorded by many sensors on many ramps in the participating states, researchers have a unique opportunity to assemble and analyze detailed data from a large sample of drivers, a variety of ramp designs, and many driving scenarios to create an extraordinarily robust dataset from which to develop conclusions and recommendations.

Table 1. Data Acquisition System Channels Collected in SHRP2 NDS. Modified from Campbell (*22*).

• Multiple videos	• Cell phone	• Vehicle network data
• Machine vision	• Seat belt information	• Accelerator
• Eyes-forward monitor	• Health checks, remote upgrades	• Brake pedal
• Lane tracker	• Illuminance sensor	• Automatic braking system
• Accelerometer data (3-axis)	• Infrared illumination	• Gear position
• Rate sensors (3-axis)	• Passive alcohol sensor	• Steering wheel angle
• GPS: latitude, longitude, elevation, time, velocity	• Incident push button—audio (only on incident push button)	• Automatic collision notification, health checks, location notification
• Forward radar	• Turn signals	• Horn
• X and Y positions	• Airbag deployment	• Many more variables
• X and Y velocities	• Speed	

To relate driver actions to roadway characteristics, additional projects within the NDS collected roadway information for the routes within the six study areas and developed a roadway information database (RID). The database combines data from state highway departments and other sources with data collected by specially equipped vans that measured roadway characteristics while traveling at posted speed limits on routes selected by SHRP2 researchers. The roadway data include the number of lanes, lane type and width, the grade, the superelevation, the beginning and end points of a curve, the curve radius, the lighting, the rumble strips, the median type, the width of the paved shoulder, the speed limit signs and their locations, the location of intersections, the number of approaches, and the traffic control devices. It is estimated that approximately 12,000 miles of roadway were measured in both directions for the sites within the six study areas; overall, approximately 72 percent of the mileage was rural and 28 percent urban, though within the Seattle area those proportions were roughly reversed (*22*).

The SHRP2 InSight Data Access Website (*23*) is a website that allows researchers to see a summary of the drivers, vehicles, trips, and event data collected during the NDS study. Researchers are able to build queries to find relations between the available variables. For example, researchers could use these queries to gauge crash severity based on vehicle classification, or find the distribution of close car-following behavior amongst drivers of different ages. This website gives access to more than 1,100 variables in 21 different data dictionaries (*24*). However, the time-series data and the majority of the video recordings collected in the NDS study are not available through the InSight website, and must be acquired through the database owners at Virginia Tech Transportation Institute (VTTI).

Summary

As critical freeway sections, loop ramps can impact safety and operations on a freeway. Loop ramps often require drivers to travel at a slower speed than other ramp types. Because of this, it is important to consider the needs of vehicles transitioning from freeway speed to the slower loop ramp speed or vice versa. There is some debate on both the best way to provide for vehicle speed change as well as the right deceleration and acceleration rates to use for exiting and entering vehicles. Through SHRP2, a naturalistic driving study, researchers are able to examine the dynamics of large quantities of vehicles on freeway loop ramps to determine the typical deceleration and acceleration rates on loop ramps.

CHAPTER III

STUDY DESIGN

The main goal of this thesis is to evaluate the impact of loop ramp design features on vehicle acceleration and deceleration. To achieve this, the researcher developed a study design that defined the general study approach, the variables of interest for the study, and the data collection, processing, and analysis procedures.

General Study Approach

The researcher had individual time-series trip data files from 1,963 trips taking place on 20 freeway loop ramps in 5 states. Of these loop ramps, nine were freeway exit ramps, where the vehicle left a higher-speed freeway heading toward a lower-speed facility, and eleven were freeway entrance ramps, where the vehicle began the ramp on a lower-speed facility and left on a higher-speed freeway. No connecting loop ramps were studied. It was anticipated that the speed change profile for vehicles traveling on entrance ramps would be different from vehicles traveling on exit ramps, so these ramp types were analyzed separately.

To evaluate the impact of ramp geometric characteristics on vehicle acceleration and deceleration, the researcher needed to know both the relevant geometrics of the freeway loop ramps and be able to locate the vehicles on the ramp from the time-series data available. To accomplish these tasks, the researcher identified relevant variables that could be obtained from Google Earth and collected this information. Once geometric data had been collected for each ramp, the researcher developed and applied a process to locate each vehicle on its respective loop ramp.

After preparing the data for analysis, the researcher used statistical analysis programs to determine the relationships between the identified variables and the speed-change rate of vehicles traveling on a loop ramp. The researcher also found and analyzed the 15^{th} and 85^{th} percentile acceleration and deceleration rates for each ramp to find the range_{15-85} of acceleration and deceleration rates on each loop ramp. For analysis, the researcher broke the ramp proper into five points and four segments, representing the quartile ramp points and four quartile segments of the loop ramp equal in length. The researcher found average, 15^{th}, and 85^{th} percentile values for speed-change rate at each point and measured the percentage of speed-change occurring on each quarter-ramp segment. Relationships were then found that could be used to predict where on a given freeway loop ramp most of the necessary speed-changing behavior would occur. Additionally, relationships were found between the ramp variables and the typical speed change rates found at each quartile point. F-tests were conducted to determine the significance of each relationship, and regression equations were formed to model speed-changing behavior on a freeway loop ramp given the most significant variables. Finally, the data were used to determine appropriate minimum auxiliary lane lengths for freeway loop ramps.

Variables of Interest

To predict speed-changing behavior on freeway loop ramps, the researcher had to determine what independent variables to analyze for impact. While the radius of curve was thought to be the most important variable when considering speed change, other variables—both geometric and characteristic—were selected for further study. The following variables were collected and analyzed for impact on vehicle speed-change rate:

- Radius of curve,
- Length of curve,
- Width of ramp lane,
- Width of ramp shoulders,
- Freeway auxiliary lane length,
- Speed limit of freeway,
- Advisory speed (for exit ramps), and
- Speed limit of crossroad.

Data Collection Methodology

After the key variables were determined, the next step for the researcher was to determine the best way of collecting data for these variables. Although the acceleration data and speed data would come from the SHRP2 time-series data, the researcher understood that most of the ramp characteristic variables would need to be obtained from other sources.

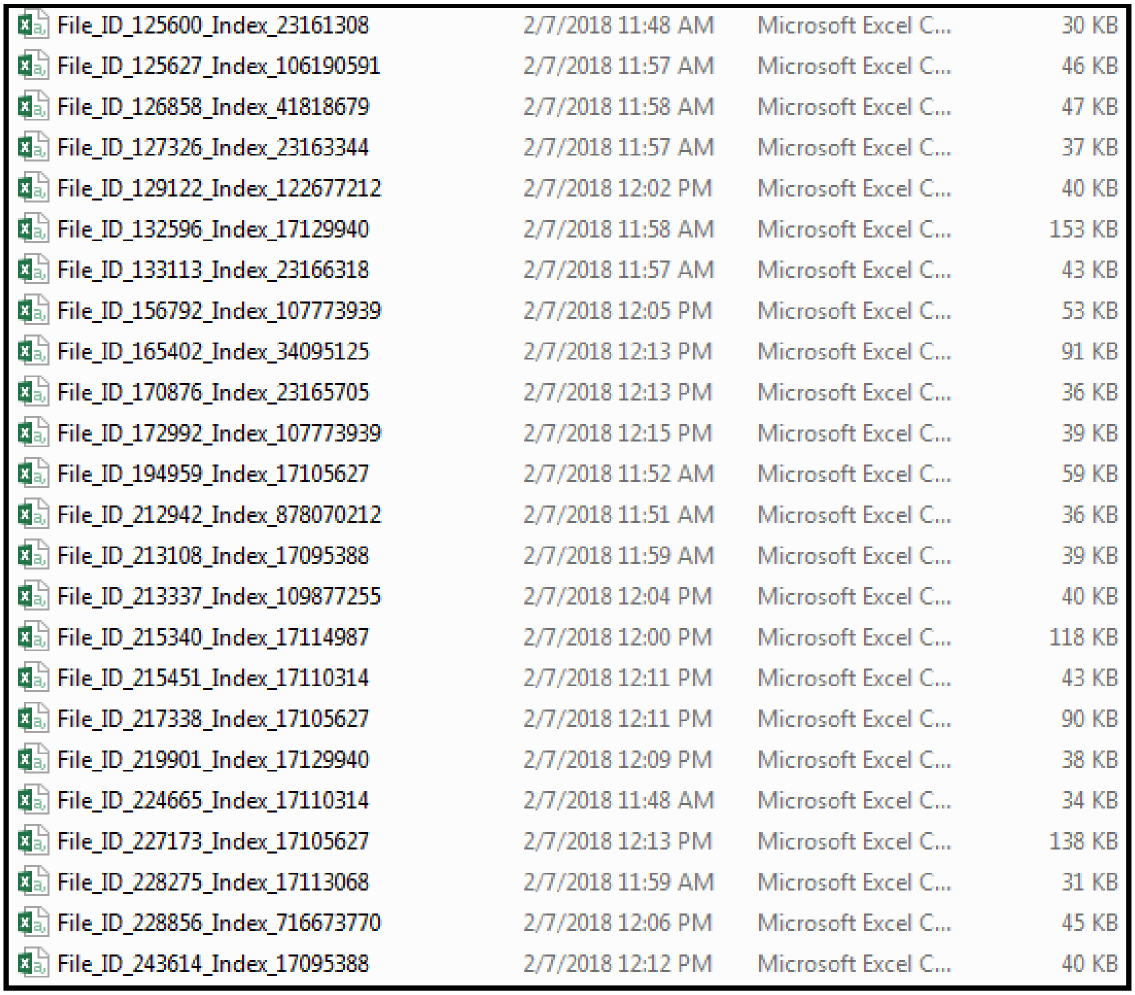
SHRP2 Time-Series Data

As part of an ongoing project, researchers selected 100 freeway ramps in the 6 states participating in SHRP2 to obtain detailed time-series data (*25*). For that project, the researchers wanted a diverse set of freeway ramps, selecting many loop, diamond, and curved ramps. Twenty of the ramps selected for that project were loop ramps. The researcher of this thesis used these twenty ramps and the data collected for these twenty ramps, for a combined total of 1,963 trips and an average of 98 trips per ramp. Because one of the ramps had only 10 trips, this ramp was removed from evaluation, leaving the researcher with 19 ramps in 5 states, with the exact breakdown of trips shown in **Table** 2. The ramp trips were well distributed between entrance and exit loop ramps, with the majority of the trips coming from Florida, North Carolina, and New York. A few trips came from ramps in Indiana and Pennsylvania, while Washington, despite being the sixth state to participate in this study, was not represented in the studied set of loop ramps. Washington relies on loop ramps less often than the other studied states, and the ones that they did have typically used a collector-distributor roadway for the weaving areas, so no loop ramps from Washington were included in the original 100 ramps.

Table 2. Number of Studied Trips by State and Direction

Sum of Number of Trips			
State	**Exit**	**Entrance**	**Total**
FL	165	464	629
IN	0	42	42
NC	552	224	776
NY	273	173	446
PA	60	0	60
Grand Total	**1050**	**903**	**1953**

Each of the 1,953 trips was given in a unique CSV file, an example of which is shown in Figure 6. Each file had time-series data, taken every one tenth of a second for the duration of the ramp, beginning two seconds before the subject entered the ramp and terminating two seconds upon exit. In addition to the time-series data, information on the vehicle year and vehicle classification was provided for each vehicle measured. In all, the SHRP2 NDS provided data on 20 variables. These variables are described in Table 3.



File_ID_125600_Index_23161308	2/7/2018 11:48 AM	Microsoft Excel C...	30 KB
File_ID_125627_Index_106190591	2/7/2018 11:57 AM	Microsoft Excel C...	46 KB
File_ID_126858_Index_41818679	2/7/2018 11:58 AM	Microsoft Excel C...	47 KB
File_ID_127326_Index_23163344	2/7/2018 11:57 AM	Microsoft Excel C...	37 KB
File_ID_129122_Index_122677212	2/7/2018 12:02 PM	Microsoft Excel C...	40 KB
File_ID_132596_Index_17129940	2/7/2018 11:58 AM	Microsoft Excel C...	153 KB
File_ID_133113_Index_23166318	2/7/2018 11:57 AM	Microsoft Excel C...	43 KB
File_ID_156792_Index_107773939	2/7/2018 12:05 PM	Microsoft Excel C...	53 KB
File_ID_165402_Index_34095125	2/7/2018 12:13 PM	Microsoft Excel C...	91 KB
File_ID_170876_Index_23165705	2/7/2018 12:13 PM	Microsoft Excel C...	36 KB
File_ID_172992_Index_107773939	2/7/2018 12:15 PM	Microsoft Excel C...	39 KB
File_ID_194959_Index_17105627	2/7/2018 11:52 AM	Microsoft Excel C...	59 KB
File_ID_212942_Index_878070212	2/7/2018 11:51 AM	Microsoft Excel C...	36 KB
File_ID_213108_Index_17095388	2/7/2018 11:59 AM	Microsoft Excel C...	39 KB
File_ID_213337_Index_109877255	2/7/2018 12:04 PM	Microsoft Excel C...	40 KB
File_ID_215340_Index_17114987	2/7/2018 12:00 PM	Microsoft Excel C...	118 KB
File_ID_215451_Index_17110314	2/7/2018 12:11 PM	Microsoft Excel C...	43 KB
File_ID_217338_Index_17105627	2/7/2018 12:11 PM	Microsoft Excel C...	90 KB
File_ID_219901_Index_17129940	2/7/2018 12:09 PM	Microsoft Excel C...	38 KB
File_ID_224665_Index_17110314	2/7/2018 11:48 AM	Microsoft Excel C...	34 KB
File_ID_227173_Index_17105627	2/7/2018 12:13 PM	Microsoft Excel C...	138 KB
File_ID_228275_Index_17113068	2/7/2018 11:59 AM	Microsoft Excel C...	31 KB
File_ID_228856_Index_716673770	2/7/2018 12:06 PM	Microsoft Excel C...	45 KB
File_ID_243614_Index_17095388	2/7/2018 12:12 PM	Microsoft Excel C...	40 KB

Figure 6. Individual trip files obtained as CSVs.

Table 3. SHRP2 Variables Provided

Variable Type	Variable	Unit or Category
Identifying	Trip ID	
	Vehicle Year	Year
	Vehicle Classification	Car/SUV_Crossover/Minivan/Pickup_Truck
Time-Series	System Time Stamp	Counts up from 1 each tenth of a second
	VTTI Time Stamp	Counts up by 100 each tenth of a second
	GPS Speed	kph
	Network Speed	kph
	Acceleration X-axis	g
	Acceleration Y-axis	g
	Acceleration Z-axis	g
	Gyro X-axis/Roll Rate	degrees per second
	Gyro Y-axis/Pitch Rate	degrees per second
	Gyro Z-axis/Yaw Rate	degrees per second
	Lane Width	cm
	Left Lane Marker Probability	1 to 1024
	Right Lane Marker Probability	1 to 1024
	Brake Pedal Position	0/1
	Gas Pedal Position	0 to 100
	Steering Wheel Position	-720 to 720 degrees
	Odometer Reading	<No data given>
	Traction Control Activation	0/1
	Electronic Stability Control Activation	0/1
	Anti-lock Braking System Activation	0/1

Supplementary Data

To supplement the time-series data, the researcher understood that additional data would be needed. To evaluate what ramp characteristics impact the braking and accelerating behavior of vehicles, ramp characteristics needed to be obtained from an outside source.

To find the ramp geometrics, the first method explored was the Roadway Inventory Database (RID). The RID is a database maintained by the Center of Transportation Research and Education at Iowa State University. It can be used to supplement the SHRP2 NDS data by providing roadway data that corresponds to routes driven during the naturalistic study. Roadway data, including alignment data, was collected through instrumented vehicles and can be accessed directly through GIS tools by matching the common Link ID. The alignment layer in this database breaks a route into segments and gives the geometric traits of superelevation, radius, distance, and lane width for each segment.

Although the RID can be a valuable resource, the researcher discovered that it could not be used to supplement the data for the thesis project. This is because, while the RID contains alignment data on much of the roadway traveled by vehicles during the study, an area where its coverage is substantially more limited are freeway ramps. Presumably, the vehicles outfitted for data collection for the RID bypassed the ramps at interchanges rather than driving on each of the four to eight ramps. Although this might have been a logical use of resources for the RID, it forced the researcher for this thesis to turn elsewhere for obtaining alignment information for each ramp.

The next method sought to obtain the geometric details of the ramps was the use of the aerial mapping tool Google Earth. The SHRP2 NDS data were collected from 2010 to

2013, so aerial photographs and street-view photographs from around this time were preferred and used when available. This measure was taken to ensure that geometric details and other ramp characteristics, such as the ramp signage, obtained from the studied ramps are as consistent as possible with what was actually experienced by the participating drivers. Using the ruler tool from Google Earth, the researcher was able to collect distance measurements as well as approximate the radii of the studied loop ramps. An example of this process is provided in Figure 7. Descriptions of all variables measured from each loop ramp through the use of Google Earth are provided in Table 4.

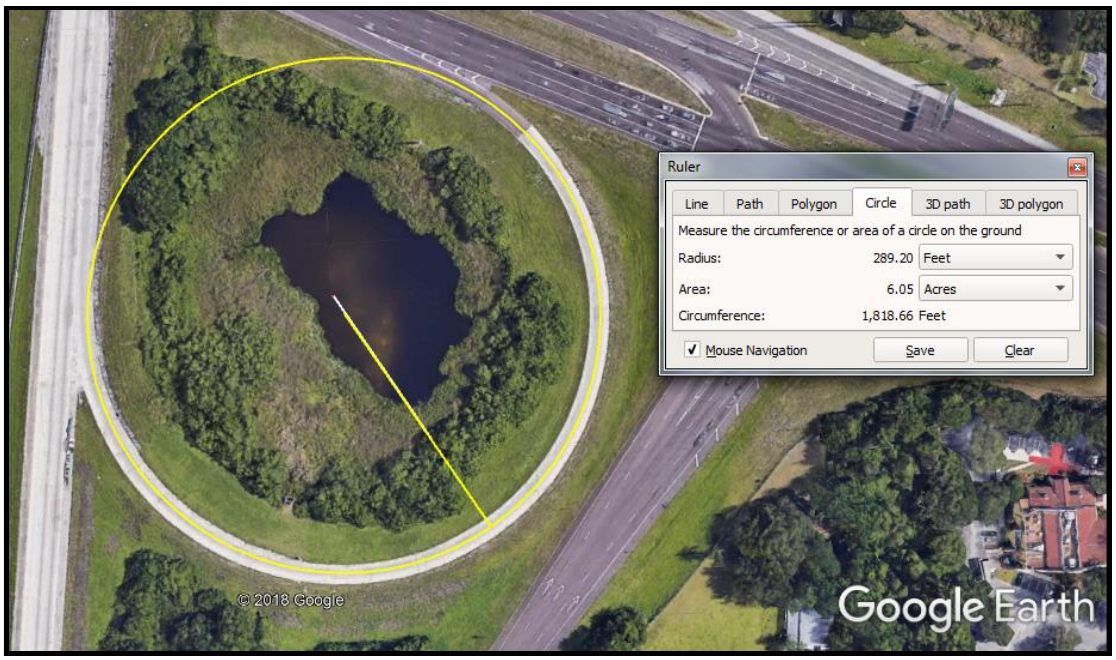


Figure 7. Example of Google Earth ruler tool.

Table 4. Ramp Characteristics Obtained from Google Earth

Location	Characteristic	Unit or Category
Highway	State	
	Name	
	Primary Direction	NB/SB/EB/WB
	Posted Speed Limit	mph
Crossroad	Name	
	Posted Speed Limit	mph
	Traffic Control at Intersection	Signal/Stop/Free Flow
Ramp Proper	Number of Ramp Segments	#
	Classification of Each Segment	Tangent/Left Curve/ Right Curve
	Length of Each Segment	ft
	Total Length of Ramp	ft
	Radius of Each Curved Segment	ft
	Deflected Angle of Each Curved Segment	Degrees
	Ramp Grade Profile	Up/Down
	Number of Lanes at Merge or Diverge Point	#
	Lane Width of Each Lane at Each Segment	ft
	Right Shoulder Width at Each Segment	ft
	Left Shoulder Width at Each Segment	ft
	Total Width of Ramp Apron at Each Segment	ft
	Presence of Advisory Speed Sign	Y/N
	Description of Advisory Speed Sign	Advisory/Chevrons
	GPS Coordinate Values for Each Ramp	Latitude, Longitude
	GPS Coordinate Values for Each Segment	Latitude, Longitude

Data Processing Methodology

Once the data was collected, the next step was to process it into a form conducive to analysis. This process required several steps, largely due to the format of the time-series data. This section details the processes applied to the data before analysis could take occur

Organizing the Data

As previously discussed, the time-series data loop ramp data came in 1,953 unique CSV files. The researcher wanted to consolidate these files into just two files: One for exit ramps and one for entrance ramps. Because these files were all in a single folder, the researcher was able to use a command function to consolidate all of these files into one file.

However, because the file did not have the LinkIDs used for the studied ramp segments, the file was still lacking a means to tie the individual lines of data to a specific ramp. Fortunately, the file names themselves contained both the individual trip's TripID and its LinkID (see Figure 6), so this problem could be solved in a similar manner involving the use of another command function. The command function, called "dir /b", could obtain all file names from a folder and convert it to a text file. The text file made through this function could be easily converted into an excel file, using underlines as delineators so that the TripID was in its own column and the LinkID was in a column, along with ".csv" attached at the end. The remaining steps of this process were to replace the ".csv" with "0" in a new column, then divide that column by 10. The result of this process can be seen in Figure 8.

dirlist.txt		TripID				LinkID
File	ID	10000601	Index	23154479.csv	231544790	23154479
File	ID	10001245	Index	21086249.csv	210862490	21086249
File	ID	100013503	Index	23165705.csv	231657050	23165705
File	ID	100013503	Index	23172592.csv	231725920	23172592
File	ID	100013765	Index	23178415.csv	231784150	23178415
File	ID	100030696	Index	23166318.csv	231663180	23166318
File	ID	10003629	Index	34092417.csv	340924170	34092417
File	ID	100036973	Index	23178415.csv	231784150	23178415
File	ID	100051760	Index	23176639.csv	231766390	23176639
File	ID	1000571	Index	122620173.csv	1226201730	122620173
File	ID	1000571	Index	23161308.csv	231613080	23161308
File	ID	10005728	Index	21054510.csv	210545100	21054510
File	ID	10006417	Index	122620173.csv	1226201730	122620173
File	ID	100068612	Index	741031881.csv	7410318810	741031881

Figure 8. Matching TripIDs with LinkIDs.

Once the researcher created an index spreadsheet containing TripIDs and their associated LinkIDs, the researcher could use Microsoft Excel's VLOOKUP function in the time-series csv files, referencing the index sheet, to search for and produce the appropriate LinkID for each trip and for each line of time-series data.

Having obtained LinkIDs for each line of time-series data, the researcher was able to use the VLOOKUP function to pull every variable ramp characteristic found through aerial photography (see Table 4) into the time-series data. This was done so that the researcher could later directly compare the acceleration values to each ramp characteristic variable. At this point, the researcher separated all data into two sheets, one for exit ramps and one for entrance ramps. This was done because the nature of speed change rate is fundamentally different on exit ramps as opposed to entrance ramps. For example, vehicles entering a high-speed freeway will accelerate more leaving a loop ramp than vehicles exiting a high-speed freeway as their target speeds are different.

Obtaining Additional Variables from the Data and Data Reduction

Equipped with time-series data from 1,934 trips along with their associated ramp characteristic variables, the researcher noted what additional data would be needed and what existing data would need to be eliminated before performing data analysis. Before the researcher could analyze the impact of ramp characteristics on vehicle dynamics, a few major questions needed to be considered:

- What acceleration time-series data should be used?
- Where data is incomplete, i.e., missing values are present in the spreadsheet, what method should be employed to fill in these values?
- Because the time-series data does not give the precise location of the vehicles on the ramps, what is the best way to know exactly where the vehicle is for each line of time-series data?

The researcher carefully examined each of these questions. The processes and rationale for answering each question are explained in this section. The final question is of particular importance as all of the time-series data is of no use if it cannot be tied to a location on the ramp.

First, the researcher considered the acceleration data. In the time-series data files received from VTTI, there were three acceleration variables corresponding to the three axes given in units of "g". See Figure 9, reprinted from the SHRP2 NDS Insight Data Dissemination Website (*23*). The x-axis acceleration would refer to the longitudinal acceleration from the vehicle slowing down or speeding up. This is the variable from the data files most commonly considered to be acceleration as it relates directly with vehicle breaking and accelerating. The y-acceleration refers to the lateral acceleration experienced by a driver around a curve. The z-acceleration is the vertical acceleration. A static vehicle would have an x, y, and z, acceleration of 0, 0, and -1 g, respectively. Because this thesis examines the impact of ramp characteristics on acceleration, the researcher decided to focus attention on x-acceleration.

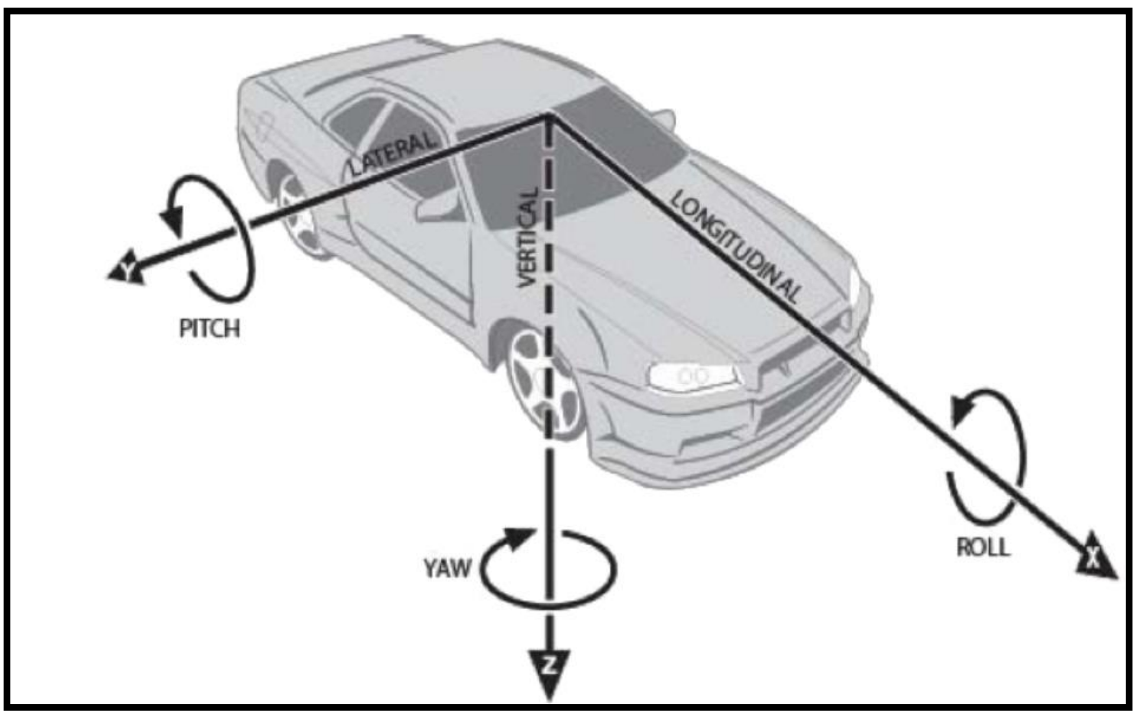


Figure 9. Acceleration axes and visualization of gyro variables from the NDS Dataset. Reprinted from the SHRP2 NDS Insight Data Dissemination Website (*23*).

Next, the author considered the missing values from the time-series data. While the time-series data received from VTTI contained network information every tenth of a second, with each tenth of a second representing one line of data, not every variable cell was filled in each line. This led to gaps in data that could either be sporadic or predictable. As an example, the GPS speed variable frequently had data only one time per second so that there were many more blank cells in the excel database than actual values. Fortunately, the presence of acceleration data was much more consistent, typically only having a few, sporadic blank cells per trip. Still, the researcher understood the need to fill in all blank cells with reasonable values and develop a process that could be applied to all other variables, including those with more frequent missing values. The researcher decided to apply a process in excel to interpolate these missing values. Because there is not a direct linear interpolation function in excel, this process was done in a series of columns. An example of this process could be seen in Figure 10. The general idea of this process was to establish the upper and lower possible bounds of acceleration rate, as determined by the nearest available acceleration data before and after the missing cell, then to apply linear interpolation to find appropriate values between the two bounds. The first step called the lower bound of the possible acceleration rate, while the second step called the upper bound. The lower bound in each case is the most recent acceleration value that was filled and the upper bound is the first filled-in acceleration value following each blank cell. In the way that the researcher defined "upper bound" and "lower bound" for this process, it is possible for the upper bound to be a smaller value than the lower bound. In fact, this would be expected when deceleration occurs, such as on exit ramps. The third step counted how many sequential missing values there were, returning a whole number when the cell was blank and the acceleration value itself when it was not. For the interpolation of acceleration values, there was typically no more than one blank cell in a row, so this gap number value was typically never greater than one.

System.Time_Stamp	vtti.accel_x	Lower Bound	Upper Bound	Gap Number (if Gap)	Consecutive Gaps Plus One	Filled X_accel
153	0.0609	0.0609	0.0609	0	1	0.0609
154	0.0667	0.0667	0.0667	0	1	0.0667
155		0.0667	0.0754	1	2	0.0711
156	0.0754	0.0754	0.0754	0	1	0.0754
157	0.0783	0.0783	0.0783	0	1	0.0783
158	0.0522	0.0522	0.0522	0	1	0.0522
159	0.0435	0.0435	0.0435	0	1	0.0435
160	0.0783	0.0783	0.0783	0	1	0.0783
161	0.0899	0.0899	0.0899	0	1	0.0899
162	0.0609	0.0609	0.0609	0	1	0.0609
163	0.0928	0.0928	0.0928	0	1	0.0928
164	0.0638	0.0638	0.0638	0	1	0.0638
165	0.0783	0.0783	0.0783	0	1	0.0783
166		0.0783	0.0609	1	2	0.0696
167	0.0609	0.0609	0.0609	0	1	0.0609
168	0.0754	0.0754	0.0754	0	1	0.0754
169	0.0841	0.0841	0.0841	0	1	0.0841
170	0.0928	0.0928	0.0928	0	1	0.0928

Figure 10. Example of interpolation processing for filling in missing time-series values.

Finally, the researcher considered the issue of locating the vehicle on the ramp. The researcher wanted to determine where on the studied ramp each vehicle was located for each line of time-series data. When researchers collect data in-field, they know with a high level of certainty where vehicles are at the time of data collection as they are able to physically observe the subject vehicles. When dealing with time-series data, the level of certainty is considerably reduced.

Had the time-series data included GPS tracking data, the task of locating each vehicle would be much easier as each line of time-series data would be directly tied to a physical location. However, across participants, each trip of time-series data should have begun at approximately the same location and ended at approximately the same location. Each trip contained a two-second buffer on each end of the ramp. In theory, the vehicle in each trip should begin traveling on the ramp at the start of the third second and leave the ramp at the end of the antepenultimate second. Given this information, it should be possible to determine the location of the vehicle simply by calculating how far the vehicle traveled beginning at the start of the third second. However, two primary issues were uncovered that prevented this simple solution from being reliable. First, there was uncertainty that the locations of the beginning and end of each ramp measured by the researcher using Google Earth were the same as those used by the database. Second, when inferring distance traveled by participants on the ramp, there were some discrepancies between trips as to how long the ramp was in total—indicating individual differences within ramps and implying that there was some sensor variation.

To begin the task of locating the vehicles, the researcher considered what time-series values could be used to pin a vehicle to a specific location. The concluding thought was that at the point of curvature and the point of tangency of each loop ramp, both the yaw rate variable and the lateral (y-) acceleration variable would noticeably change. The researcher believed that it would be possible to use the time-series data to identify these “transition points” for each vehicle.

To identify the transition points of the curve, the researcher used Equation 2, which relates the velocity and yaw rate of a vehicle to the radius of curve.

$$Radius\ of\ turn = \frac{Velocity}{Yaw\ Rate} \tag{2}$$

Where: Radius of turn in feet,

Velocity in feet per second, and

Yaw rate in radians per second.

After converting the given vehicle speed to feet per second and the given yaw rate to radians per second for each line of time-series data, the researcher was able to determine the radius of the turn as driven by the vehicle. The radius of turn found via this formula (the “inferred radius”) can differ from the actual radius for a couple of reasons. First, drivers are not required to drive on curves in the same way. For example, a vehicle that cuts into right shoulder while on a curve will have a different radius of turn than a vehicle that cuts into the left shoulder. Second, increasing superelevation reduces the yaw rate necessary to make a turn, thereby resulting in an overestimated radius of curve. The effect of superelevation could be seen in many trips, where the minimum radius of turn driven by the vehicle was larger than the radius estimated from Google Earth.

Because each loop ramp had a beginning tangent, followed by a sharp curve, followed by an ending tangent, the researcher reasoned that the vehicles could be located by applying the following procedure:

1. Calculate the inferred radii of the curve for each line of data (feet per 0.1 second divided by radians per 0.1 second).
2. Compare the inferred radii to the radii already measured.
3. Set a "threshold of turning" to establish when the vehicle moves from the tangent to the curve and then back to the tangent.
4. Calculate the measured distance traveled on the loop segment for several trips given the threshold of turning.
5. Compare these distances to the distance already observed and evaluate if the calculated distance is close enough to the measured distance.
6. If not, return to step 3 and adjust the "threshold of turning" accordingly.

An example of the first two steps is given in Figure 11. The goal of these steps was to compare the observed ramp curvature to the curvature experienced by the vehicles. Once these steps were finished, a "threshold of turning" could be set that could be applied to each trip to evaluate when the subject vehicle began and ended its turn. The threshold of turning was set as a multiple of the observed radius of curve and was used to denote a switch from one segment to the next. It could be set either to determine the switch from a tangent section (or lower curvature section) to a higher curvature section or from a higher curvature section to a tangent section (or lower curvature section). If the threshold of turning was set to 1.0 (or the actual radius of the curve), a segment change would only be denoted once the radius of the circle driven by the vehicle was equal to the circle's actual radius. Because of individual differences in the way drivers navigate a curve, it would not be prudent to set the threshold to 1.0. Indeed, it is possible to navigate an entire loop ramp without ever reaching the threshold of 1.0, even without considering the effect of superelevation. A vehicle that navigates a loop ramp like racecar drivers navigate tight turns—beginning the loop ramp in the left-hand side of its lane, cutting into the right for the sharpest point of the curve, then finishing the loop ramp back in the left-hand side of its lane—drives a circle with a larger radius than a car that stays on the centerline for the duration of the curve. For the purpose of this project, it was found that a threshold of 3.0 was a reasonable starting place for this step. An example of this process is given in Figure 12.

System.Time_Stamp	Filled Speed (kph)	Filled Speed (fps)	Filled Yaw Rate Moving Average (deg/sec)	Filled Yaw Rate (rad/sec)	Inferred Radius (ft)	Radius of Curve1 (ft)
30	39.00	35.54	2.424	0.01231	840	177
31	39.00	35.54	2.868	0.05005	710	177
32	39.00	35.54	3.370	0.05882	604	177
33	38.00	34.63	3..784	0.06605	524	177
34	38.00	34.63	4.168	0.07275	476	177
35	37.00	33.72	1.582	0.07998	422	177
36	37.00	33.72	4.967	0.08668	389	177
37	37.00	33.72	5.410	0.09442	357	177
38	37.00	33.72	5.706	0.09958	339	177
39	37.00	33.72	6.001	0.10474	322	177
40	37.00	33.72	6.179	0.10474	313	177
41	37.00	33.72	6.297	0.10990	307	177
42	37.00	33.72	6.386	0.11145	303	177
43	37.00	33.72	6.445	0.11248	300	177
44	37.00	33.72	6.622	0.11558	292	177
45	37.00	33.72	6.800	0.11867	284	177
46	37.00	33.72	6.918	0.12074	279	177
47	37.00	33.72	7.066	0.12332	273	177

Figure 11. Example of inferred radii calculation.

System.Time_Stamp	Inferred Radius (ft)	Radius of Curve1 (ft)	Threshold of Turning	Identifying Segment
30	840	177	3.0	Tangent
31	710	177	3.0	Tangent
32	604	177	3.0	Tangent
33	524	177	3.0	Curve
34	476	177	3.0	Curve
35	422	177	3.0	Curve
36	389	177	3.0	Curve
37	357	177	3.0	Curve
38	339	177	3.0	Curve
39	322	177	3.0	Curve
40	313	177	3.0	Curve
41	307	177	3.0	Curve
42	303	177	3.0	Curve
43	300	177	3.0	Curve
44	292	177	3.0	Curve

Figure 12. Using the threshold of turning to determine segment transition.

By finding the both the starting and ending point of the curve, it was possible to measure the distance the vehicle covered while assumed to be traveling on the curve section (step 4). The average calculated distance of 10 or more trips was taken for each ramp and then compared with the measured distance (step 5). If the measured distance was within 5 percent of the calculated distance, the researcher accepted the threshold as reasonable and could estimate the starting point of each curve by again averaging the total distance traveled by 10 or more trips upon reaching the beginning of the curve. If the measured distance was not within 5 percent of the calculated distance, the researcher moved on to step 6 and adjusted the threshold of turning for reevaluation.

This process worked well and could be adjusted to determine transitions from one curve to another curve of different radii by adjusting the threshold to look for a radii somewhere in between the two curves. Once the starting point of a ramp segment was determined, the starting point of each subsequent segment could be found by adding the distance measured from Google Earth. Finally, each row of time-series data was tied to its associated ramp segment so that all geometric characteristics observed could be directly tied to each line of time-series data. Once this process was done for all ramps, the vehicle dynamics could be tied to the geometric characteristics of the ramps and the data was ready for analysis.

Data Analysis Methodology

Although the researcher split the data into entrance loop ramps and exit loop ramps, many of the data analysis procedures implemented on each subset were largely similar. First, the researcher wanted to find where on the ramps vehicles were accelerating and decelerating. Moreover, the researcher was interested in finding what portion of vehicle acceleration and deceleration occur on the loop ramp itself as opposed to the freeway and auxiliary lanes. This portion will be referred to as the speed-change ratio and is the ratio of the acceleration or deceleration occurring on a ramp segment divided by the total acceleration or deceleration needed for the vehicle to go from its initial speed to its target speed. To find the speed-change ratio, the researcher divided the ramp into four equal-length ramp quarters, beginning at the point of curvature (PC) of the loop ramp and concluding at its point of tangency (PT). In addition to these four segments, the freeway and auxiliary lanes were considered together as an additional segment. They were taken together as one segment because little vehicle dynamic data was available for auxiliary lanes, so attaining an accurate estimate on the vehicle's acceleration or deceleration on auxiliary lanes was not possible.

A large speed-change ratio for the freeway and auxiliary lane suggests the importance of an auxiliary lane to accommodate drivers' speed-change needs. An important note is that for a vehicle trip to be used for this purpose, the vehicle needed to have data at each quarter point of the ramp. For exit ramps, this reduced the number of trips to 734 complete trips on 8 ramps. For entrance ramps, the number of complete trips was 664 on 8 ramps. Details about these ramps are provided in Table 5.

Table 5. Basic Characteristics of the 16 Studied Loop Ramps.

Exit Ramp Number	**n**	**Min Radius (ft)**	**Freeway Speed Limit (mph)**	**Advisory Speed (mph)**	**Intersection Traffic Control**	**Ramp Length (ft)**	**Average Lane Width (ft)**
1	81	140	55	25	Signal	844	15.0
2	108	150	60	25	Free Flow	735	15.0
3	102	155	65	25*	Signal	890	11.0
4	180	185	65	25	Free Flow	971	12.0
5	70	190	55	30	Free Flow	1320	13.0
6	34	230	70	25	Signal	825	14.0
7	130	230	55	25*	Free Flow	975	12.5
8	74	325	70	25	Free Flow	1705	14.0
Entrance Ramp Number	**n**	**Min Radius (ft)**	**Freeway Speed Limit (mph)**	**Crossroad Speed Limit (mph)**	**Intersection Traffic Control**	**Ramp Length (ft)**	**Average Lane Width (ft)**
1	98	150	55	40	Free Flow	1500	15.5
2	45	160	60	45	Free Flow	1055	14.0
3	55	165	65	45	Signal	930	18.0
4	50	175	65	45	Signal	805	17.0
5	75	175	55	40	Free Flow	955	13.0
6	43	185	60	40	Signal	901	15.5
7	55	230	70	45	Signal	920	16.0
8	192	320	70	45	Signal	1215	14.5

*Advisory speed not present on ramp, estimated using the Green Book (*6*)

The researcher was interested in finding the portion of acceleration or deceleration that occurs on each of these five segments for each ramp. The researcher wanted to know both the average ratio and the range_{15-85} of speed-change ratio for each ramp. To get the range_{15-85}, the 15^{th} and 85^{th} percentile speed-change ratios were taken for each ramp. Statistical analysis was performed on both the average and 85^{th} percentile speed change ratios so that models could be constructed using data analysis software. The models were made to predict both the speed-change ratios for each freeway loop ramp segment based on the variables of interest. Finally, coefficients of determination were found and significance tests were performed for each model.

Next, the researcher analyzed the data by quarter point of the ramp to find the average and range_{15-85} (again, 15^{th} to 85^{th} percentile) speed change rate. Histograms were made to show the distribution of acceleration and deceleration at each quarter point of each studied ramp. The 85^{th} percentile speed-change rate values could then be compared to the commonly-used deceleration and acceleration values to determine whether the studied speed-change values on the freeway loop ramps are acceptable. Again, statistical analysis was performed on both the average and 85^{th} percentile speed-change rate at each quarter point to develop predictive models. Coefficients of determination were found and significance tests were performed for each model.

Differences between Exit and Entrance Ramps

For each ramp, vehicles had a starting speed and a target speed. These speeds, in conjunction with the vehicle speeds at each quarter point of the ramp, were used to determine where the acceleration or deceleration necessary to go from the starting speed to the target speed was occurring. For exit ramps, the starting speed was considered to be the freeway speed limit, while the ramp's advisory speed was selected as the target speed. In each case for exit ramps, the target speed was less than the starting speed, so deceleration over the course of the ramp was anticipated. Two of the ramps did not have advisory speeds visible to the researchers. In comparing the minimum radii of these ramps to the minimum radii of ramps with known posted speed limits, an advisory speed of 25 mph appears to be a reasonable estimate. To verify this, the researcher consulted the Green Book (*6*). Table 3-7 in the Green Book indicates that curves with a superelevation of 6 or 8 percent, and radii between 134 and 231 ft should have a design speed of 25 mph. Both of the radii for the ramps lacking advisory speeds fall within this range, so it is likely that if they had an advisory speed posted, that it would be 25 mph.

To find the ratio of deceleration occurring on each ramp quarter of each exit loop ramp, the researcher used the vehicle speeds at each ramp quarter point. The researcher took the speed difference between the two quarter points and divided it by the total speed difference necessary to slow from the initial speed (the freeway speed limit) to the target speed (the ramp advisory speed). To find the freeway's deceleration ratio on exit ramps, the researcher took the difference between the freeway speed limit and the vehicle's speed at the PC, then divided this by the total speed difference necessary to slow from the initial speed to the target speed.

For entrance ramps, the crossroad speed was used as the initial speed and the freeway speed limit was used as the target speed. The crossroad speed was used as most of the entrance loop ramps were free-flowing, and the crossroad speed provided a good baseline for a speed appropriate before entering the loop ramp. While the acceleration ratio on each entrance loop ramp was done in the same manner as with exit ramps, the freeway acceleration ratio was found by taking the difference between the vehicle's speed at the end of the fourth quarter-segment (the ramp's PT) and the target speed, then once again dividing by the speed difference between the target speed and the initial speed.

Measures of Effectiveness

When examining these loop ramps, the primary measure of effectiveness was how closely the observed acceleration and deceleration rates experienced on the loop ramp reflect the "normal" acceleration rates used in the industry. Individual deviations from these normal values could indicate that some characteristics of the loop ramp are contributing to different speed-changing rates while. If many of the ramps deviate from these values, it could indicate the need for updating the acceleration and deceleration rate assumptions for freeway loop ramps.

To examine where on loop ramps speed changing behavior occurs, the researcher is introducing two new concepts: deceleration ratio for exit loop ramps and acceleration ratio for entrance loop ramps. To find the values, equations 3 and 4 are provided:

$$DR_{segment} = \frac{SD_{segment}}{SD_{ramp}} \tag{3}$$

$$AR_{segment} = \frac{SD_{segment}}{SD_{ramp}} \tag{4}$$

Where: $\mathrm{DR_{segment}}$ = Deceleration ratio on segment, decimal;

$\mathrm{AR_{segment}}$ = Acceleration ratio on segment, decimal;

$SD_{segment}$ = Speed difference from beginning to end of segment, mph;

SD_{ramp} = Speed difference between initial speed and target speed on ramp, mph.

In this thesis, the researcher conducted statistical analysis to develop models that predict the deceleration ratio and acceleration values on the freeway ramps. To show the strength of these models, the researcher provides the results of the statistical analysis, including R-square values and F-test scores for each model.

CHAPTER IV

RESULTS

Location of Acceleration and Deceleration

Before determining which variables were the most influential on speed-change rate for freeway loop ramps, the researcher wanted to know where on each ramp vehicles change speed. The findings of this effort are provided in this section, broken down by exit ramps and entrance ramps.

Exit Ramps

For exit loop ramps, it was found that about two-thirds of all vehicle deceleration necessary to go from the freeway speed to the advisory speed occurs before the vehicle even gets to the PC of the loop ramp. This means that much of the deceleration occurs on either the freeway or the auxiliary lanes. Vehicles on the first quarter of the ramp (Q1), decelerate an average of nearly one-sixth of the necessary deceleration. Meanwhile, ramp Q2 and Q3 do not follow a consistent trend and average very little deceleration. The last quarter of the ramp, Q4, typically sees some acceleration as vehicles exit the curve. The results by ramp can be seen in Table 6. Table 7 and Figure 13 can be viewed in conjunction with Table 6 for an easier visualization of vehicle speed at each of the five ramp locations. It is worth noting that not all vehicles experienced 100 percent of the necessary deceleration to slow from the freeway speed limit to the ramp advisory speed. In fact, if the average deceleration ratios are summed for the freeway and the first three ramps quarters (before the average vehicle begins accelerating), the value is only 87.5 percent, and is even lower on some ramps. This shows that vehicles do not always slow down to the target, or advisory speed on exit loop ramps. Additionally, it means that when considering the deceleration that actually occurs during the transition from the freeway to the ramp proper, the proportion experienced on the freeway and on Q1 is higher. This process also assumed that vehicles began by traveling the speed limit on the freeway. If, however, a vehicle was traveling more than or less than the speed limit, the freeway deceleration ratio would be higher or lower, respectively.

Table 6. Average Deceleration Ratio for Each Exit Ramp Segment

Exit Ramp	Min Radius (ft)	Fwy SL (mph)	Advisory Speed (mph)	Deceleration Ratio (%)				
				Freeway	Q1	Q2	Q3	Q4
1	140	55	25	67.1% (19%)**	23.3% (16%)	0.4% (8%)	2.2% (11%)	6.6% (20%)
2	150	60	25	76.5% (11%)	16.3% (6%)	1.0% (5%)	-4.9% (6%)	-16.4% (6%)
3	155	65	25*	49.7% (14%)	29.5% (10%)	9.2% (10%)	-6.2% (9%)	7.9% (13%)
4	190	65	25	68.6% (11%)	17.7% (9%)	4.6% (6%)	2.9% (8%)	-10.7% (8%)
5	190	55	30	70.4% (14%)	17.4% (10%)	-6.5% (9%)	17.0% (17%)	-34.8% (18%)
6	230	70	25	61.2% (10%)	11.0% (8%)	6.0% (7%)	-0.4% (5%)	18.1% (13%)
7	230	55	25*	79.1% (10%)	3.8% (8%)	-0.4% (5%)	12.3% (17%)	-7.3% (23%)
8	325	70	25	61.6% (15%)	8.3% (10%)	2.1% (5%)	-0.8% (7%)	-13.7% (8%)
Average				**66.8%**	**15.9%**	**2.0%**	**2.8%**	**-6.3%**

*Advisory speed not present on ramp, estimated using the Green Book (*6*)

**Standard deviation in parentheses

Table 7. Average Vehicle Speed by Ramp Location

Exit Ramp	Min Radius (ft)	Fwy SL (mph)	Advisory Speed (mph)	Average Vehicle Speed by Location (mph)				
				PC	25	50	75	PT
1	140	55	25	34.9 (5.8)**	27.9 (3.7)	27.8 (3.1)	27.1 (4.5)	25.1 (7.8)
2	150	60	25	33.2 (3.7)	27.5 (3.4)	27.2 (3.4)	28.9 (3.9)	34.6 (4.1)
3	155	65	25*	45.1 (5.9)	33.3 (4.5)	29.6 (3.1)	32.1 (5.3)	29.0 (7.3)
4	190	65	25	37.6 (4.4)	30.5 (3.6)	28.6 (4.0)	27.5 (4.8)	31.8 (4.8)
5	190	55	30	37.4 (3.4)	33.1 (3.3)	34.7 (3.8)	30.4 (5.3)	39.1 (4.5)
6	230	70	25	42.5 (4.4)	37.5 (3.1)	34.8 (4.1)	35.0 (5.3)	26.8 (9.2)
7	230	55	25*	31.3 (3.4)	30.1 (3.1)	30.3 (3.5)	26.6 (5.6)	28.8 (7.0)
8	325	70	25	42.3 (6.9)	38.5 (4.2)	37.6 (4.3)	38.0 (5.3)	44.1 (5.3)
Averag				**38.0**	**32.3**	**31.3**	**30.7**	**32.4**

*Advisory speed not present on ramp, estimated using the Green Book (*6*)

**Standard deviation in parentheses

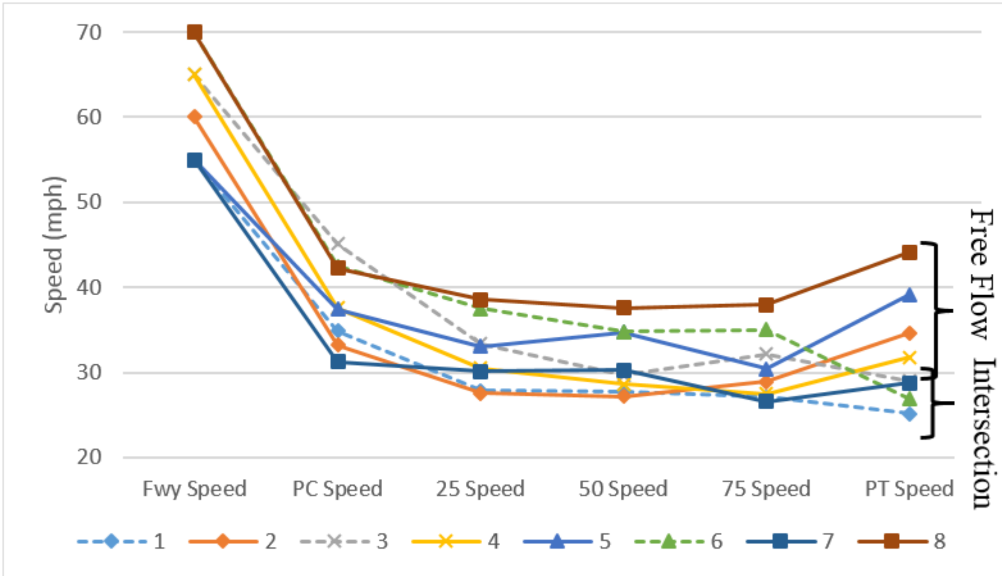


Figure 13. Average vehicle speed on exit loop ramp by ramp number.

It can be seen from Figure 13 that the vehicles largely follow the same speed trajectories on the different ramps studied, with some variation leaving the ramp. As shown in Table 5, ramps 1, 3, and 6 terminate at an intersection rather than being exclusively free-flowing. The PT speed on these three ramps is shown to decrease, while the PT speed on the other five ramps increases. This helps to explain some of the variation seen between the ramps at the ramp PT.

In addition to finding the average deceleration ratio for each ramp quarter, the researcher was interested in finding the range_{15-85} of freeway exit ramps. To measure the range_{15-85} of deceleration experienced by the vehicle on each of the ramp segments and the freeway, the 15th and 85th percentile deceleration ratios were taken for each ramp from the disaggregate trip data. These results are provided in Table 8 and indicate that most vehicles will achieve anywhere from roughly 55 to 80 percent of their necessary deceleration on the freeway/auxiliary lane part of the ramp, before they get to the PC of the loop.

Table A-1 in Appendix shows the associated range_{15-85} of speeds at each ramp point. Although the 15th percentile deceleration ratio for Q1 of the ramp was less than 10 percent, the 85th percentile deceleration ratio was 25 percent. This means that 15 percent of drivers perform at least 25 percent of their deceleration on Q1 of the ramp, after the loop ramp has already begun. This shows that although much of the deceleration will occur before the loop ramps begins, considerable deceleration can occur on Q1 of an exit loop ramp. This is equivalent to a deceleration of approximately 9 mph. The range_{15-85} of the deceleration ratio for Q2, Q3, and Q4 hovers closer to zero and spans both positive and negative values. In other words, it is common for vehicles to either slow down or speed up, but not by that much, along the latter three quarters of exit loop ramps. Interestingly, the deceleration ratio range_{15-85} narrows for vehicles on Q2 and is widest for vehicles entering and exiting the loop ramp, indicating again that these road segments have the most variability. In general, these results show that the vast majority of loop ramp deceleration occurs either before the vehicle reaches the loop ramp or on the first quarter of the ramp.

Table 8. Range$_{15-85}$ of Deceleration Ratio for Each Exit Ramp Segment

Exit Ramp	Min Radius (ft)	Fwy SL (mph)	Adv Speed (mph)	Deceleration Ratio Range (%)				
				Freeway	**Q1**	**Q2**	**Q3**	**Q4**
1	140	55	25	52.4%-83.0%	11.5%-40.9%	-6.7%**-5.5%	-6.8%-10.5%	-10.9%-31.0%
2	150	60	25	64.9%-86.2%	10.2%-22.3%	-3.7%-6.0%	-10.4%-1.2%	-23.0%--9.0%
3	155	65	25*	39.2%-62.1%	20.4%-39.1%	-0.3%-20.0%	-11.3%--2.5%	-3.1%-18.8%
4	190	65	25	57.5%-80.1%	9.3%-25.8%	-1.5%-11.5%	-4.3%-10.5%	-17.3%--4.0%
5	190	55	30	55.9%-84.5%	7.9%-27.0%	-16.8%-2.5%	0.8%-33.8%	-47.3%--20.5%
6	230	70	25	50.8%-72.4%	4.7%-17.4%	-1.9%-11.1%	-6.5%-5.4%	7.2%-35.9%
7	230	55	25*	70.3%-87.9%	-2.2%-11.5%	-5.2%-4.6%	-0.4%-26.7%	-26.3%-10.3%
8	325	70	25	44.0%-76.0%	-0.8%-16.3%	-2.7%-6.9%	-7.3%-7.9%	-21.3%--3.8%
Average				**54.4%-79.0%**	**7.6%-25.0%**	**-4.9%-8.5%**	**-5.8%-11.7%**	**-17.7%-7.3%**

*Advisory speed not present on ramp, estimated using the Green Book (*6*)

** Negative numbers indicate acceleration on the ramp quarter

Entrance Ramps

The researcher found that on entrance loop ramps, vehicles must accelerate considerably after the PT of the ramp. In fact, the average speed of vehicles crossing the PT of the entrance ramp was only 40.0 mph and was typically lower than the speed limit of the crossroad. In Table 9, it is shown that the average acceleration ratio of the freeway and auxiliary lane averages more than 100 percent. This means that the average speed-change needed to reach the freeway speed limit is greater than the difference of the freeway speed limit and the crossroad speed limit and indicates that a speed lower than the crossroad speed limit would likely be more appropriate for the initial speed. Another way to think about this is that the average speed of vehicles exiting the loop ramp is lower than the crossroad speed limit. Of course, the average vehicle did not begin the ramp traveling at the crossroad speed limit, but was instead traveling slightly under 30 mph. See Table 10 and Figure 14 for vehicle speed at each ramp quarter point. This table shows that vehicles on entrance loop ramps follow a similar pattern to vehicles on exit loop ramps—with much of the speed changing occurring either on the freeway itself or on the quarter of the ramp nearest the freeway. Moreover, the quarter of the ramp nearest the crossroad experienced a higher variability of acceleration, while the middle two ramp quarters had less speed-changing. On the entrance ramps, vehicles on the final quarter of the ramp experienced an average acceleration of 5.4 mph, while the average vehicle would need to undergo an average acceleration of about four times that (22.5 mph) after the ramp PT to reach the freeway speed limit.

Table 9. Average Acceleration Ratio of Each Entrance Ramp Segment

Ramp	Min Rad (ft)	Fwy SL (mph)	Cross-road SL (mph)	Acceleration Ratio (%)				
				Q1	Q2	Q3	Q4	Freeway
1	150	55	40	50.7% (28%)*	-24.7% (26%)	14.0% (21%)	39.3% (22%)	94.7% (29%)
2	160	60	45	-24.0% (28%)	22.7% (16%)	-18.7% (13%)	34.0% (18%)	176.0% (21%)
3	165	65	45	44.0% (16%)	-5.0% (16%)	21.5% (15%)	30.5% (16%)	128.5% (28%)
4	175	65	45	16.5% (12%)	12.5% (10%)	20.0% (11%)	31.0% (14%)	132.5% (25%)
5	175	55	40	8.0% (18%)	12.0% (11%)	18.7% (14%)	36.7% (17%)	104.0% (28%)
6	185	60	40	2.0% (12%)	-12.0% (12%)	17.0% (16%)	24.5% (17%)	113.0% (32%)
7	230	70	45	21.2% (11%)	13.2% (9%)	17.6% (9%)	22.0% (10%)	98.0% (20%)
8	320	70	45	-2.0% (8%)	-0.8% (7%)	11.2% (12%)	15.6% (16%)	98.0% (26%)
Average				**14.5%**	**2.2%**	**12.7%**	**29.2%**	**118.1%**

*Standard deviation in parentheses

The researcher was also interested in finding the acceleration ratio range_{15-85} for each ramp segment. These values can be seen in Table 11. Additionally, Table A-2 in Appendix A provides details on vehicle speeds at each ramp quarter point.

Table 10. Average Vehicle Speed by Entrance Ramp Location

Ramp	Min Rad (ft)	Fwy SL (mph)	Cross-road SL (mph)	Average Vehicle Speed by Location (mph)				
				PC	25	50	75	PT
1	150	55	40	28.9 (5.2)*	36.5 (4.0)	32.8 (4.5)	34.9 (3.8)	40.8 (4.3)
2	160	60	45	31.5 (5.1)	27.9 (3.1)	31.3 (3.4)	28.5 (3.2)	33.6 (3.2)
3	165	65	45	21.2 (5.7)	29.9 (4.3)	29.0 (4.4)	33.2 (4.3)	39.3 (5.5)
4	175	65	45	22.6 (2.8)	25.9 (3.0)	28.4 (2.7)	32.3 (3.5)	38.5 (5.0)
5	175	55	40	28.1 (5.4)	29.2 (4.3)	31.0 (4.1)	33.8 (3.9)	39.4 (4.1)
6	185	60	40	31.2 (3.1)	31.5 (3.0)	29.1 (3.3)	32.5 (4.4)	37.4 (6.4)
7	230	70	45	27.1 (3.8)	32.3 (3.1)	35.7 (3.7)	40.0 (3.8)	45.5 (5.1)
8	320	70	45	39.5 (5.1)	39.1 (4.6)	38.9 (4.6)	41.7 (4.6)	45.5 (6.4)
Average				**28.8**	**31.6**	**32.0**	**34.6**	**40.0**

*Standard deviation in parentheses

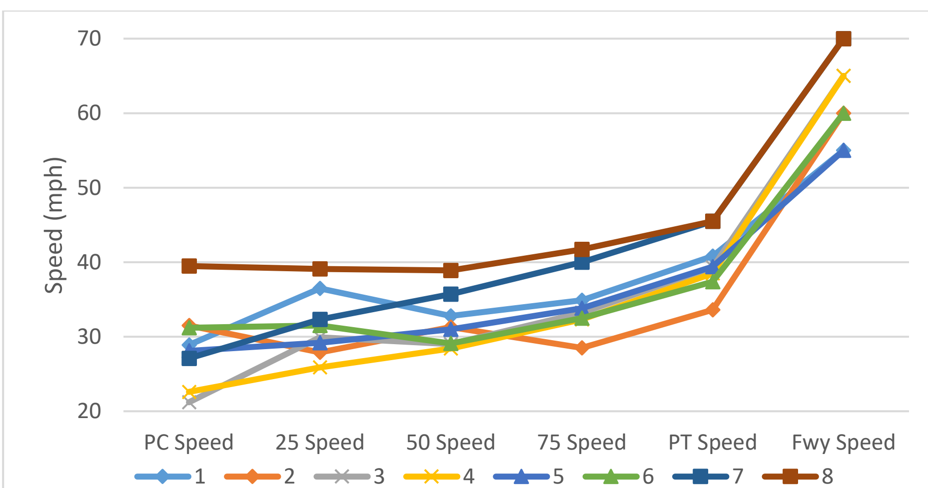


Figure 14. Average vehicle speed on entrance loop ramp by ramp number.

Table 11. Acceleration Ratio Range$_{15-85}$ for Each Entrance Ramp Segment

Entrance Ramp	Min Radius (ft)	Fwy SL (mph)	Cross-road SL (mph)	Acceleration Ratio Range (%)				
				Q1	Q2	Q3	Q4	Freeway
1	140	55	40	17.9% 79.7%	-41.3% -4.6%	-2.4%** 27.0%	20.6% 56.5%	67.4% 118.5%*
2	150	60	45	-54.4% 1.1%	7.2% 38.2%	-33.1% -3.5%	16.3% 51.8%	146.7% 198.2%
3	155	65	45	27.3% 59.1%	-13.6% 7.9%	11.0% 34.9%	19.8% 43.8%	104.0% 156.6%
4	190	65	45	5.9% 31.4%	1.4% 21.8%	10.7% 29.0%	17.5% 43.4%	108.9% 159.2%
5	190	55	40	-11.5% 27.7%	0.4% 23.6%	2.7% 31.1%	25.8% 53.6%	75.2% 130.6%
6	230	70	40	-11.1% 15.7%	-22.9% 0.0%	6.2% 29.1%	15.2% 36.6%	87.6% 129.8%
7	230	55	45	11.5% 32.0%	6.9% 19.4%	10.6% 27.4%	17.8% 29.8%	77.5% 120.9%
8	325	70	45	-10.7% 8.1%	-9.3% 6.7%	-4.0% 21.5%	-4.2% 29.5%	67.4% 122.7%
Average				**-3.1%** **31.8%**	**-8.9%** **14.1%**	**0.2%** **24.6%**	**16.1%** **43.1%**	**91.9%** **142.1%**

*A vehicle with more than 100 % of necessary acceleration occurring on the freeway would be traveling slower than the crossroad speed limit at the end of the ramp

** Negative numbers indicate deceleration on the ramp quarter

Although the acceleration ratio range$_{15-85}$ on entrance ramps is consistently larger than the deceleration ratio range$_{15-85}$ on exit ramps, it is important to note that the two measures are fundamentally different. Though each attempts to measure the ratio of the speed-change required to go from an initial speed to a target speed, they each use different measures for what the current speed and the target speed are. For entrance ramps, the current speed used was the crossroad speed limit. However, many vehicles began the ramps traveling well under this speed, with the average vehicle crossing the PC about 15 mph under the crossroad speed limit. In fact, although all of the entrance ramps had free-flowing right-turn lanes into the ramp proper, many of the ramps were signalized, letting additional vehicles enter from the intersection, generally turning left from the crossroad. Many of these vehicles would be entering the ramp at a slower pace, contributing to the lower average PT speed.

Because the acceleration ratio values were higher than the deceleration ratio values, the researcher noted that speed differentials between every two quarter points were a more intuitive way to see and evaluate where acceleration is occurring on an entrance loop ramp. The average and 85th percentile speed differentials were based on the disaggregate data for each ramp, and are provided in Table 12 and Table 13, respectively.

Table 12. Average Speed Differential by Ramp Segment

Exit Ramp	Min Radius (ft)	Fwy SL (mph)	Advisory Speed (mph)	Speed Differential (mph)				
				Q1	Q2	Q3	Q4	Freeway
1	150	55	40	7.6	-3.7	2.1	5.9	14.2
2	160	60	45	-3.6	3.4	-2.8	5.1	26.4
3	165	65	45	8.8	-1.0	4.3	6.1	25.7
4	175	65	45	3.3	2.5	4.0	6.2	26.5
5	175	55	40	1.2	1.8	2.8	5.5	15.6
6	185	60	40	0.4	-2.4	3.4	4.9	22.6
7	230	70	45	5.3	3.3	4.4	5.5	24.5
8	320	70	45	-0.5	-0.2	2.8	3.9	24.5
Average				**2.8**	**0.5**	**2.6**	**5.4**	**22.5**

Table 13. 85th Percentile Speed Differential by Ramp Segment

Exit Ramp	Min Radius (ft)	Fwy SL (mph)	Adv Speed (mph)	Speed Differential (mph)				
				Q1	Q2	Q3	Q4	Freeway
1	150	55	40	11.9	-0.7	4.0	8.5	17.8
2	160	60	45	0.2	5.7	-0.5	7.8	29.7
3	165	65	45	11.8	1.6	7.0	8.8	31.3
4	175	65	45	6.3	4.4	5.8	8.7	31.8
5	175	55	40	4.2	3.5	4.7	8.0	19.6
6	185	60	40	3.1	0.0	5.8	7.3	26.0
7	230	70	45	8.0	4.9	6.9	7.4	30.2
8	320	70	45	2.0	1.7	5.4	7.4	30.7
Average				**5.9**	**2.6**	**4.9**	**8.0**	**27.1**

Rates of Acceleration and Deceleration

With the knowledge of where speed-changing typically occurs on freeway loop ramps, the researcher was interested in the actual rates of acceleration and deceleration occurring on each ramp. To find these values, the researcher considered average vehicle speed change rate on each ramp quarter as well as on each of the five associated quarter points. While finding instantaneous values at points is similar to finding the average acceleration or deceleration values over each ramp quarter, doing both can help complete the picture of speed change rates on ramps and could help to see whether acceleration and deceleration rate on ramps is roughly constant. To find the average rate of acceleration or deceleration along a section of the ramp, the researcher divided the individual vehicle's speed change (in ft per sec) by the time the vehicle was on the ramp section (in sec). Once the rates of speed change—both the average and the range_{15-85}—were found for each ramp, the researcher could later perform statistical analyses and model speed change rate based on the ramp variables.

Finally, these values could be compared to the normal acceleration and deceleration values found in literature.

Exit Ramps

First, the researcher wanted to find the average deceleration values over each ramp quarter. The values for each ramp and for each ramp quarter are shown in Table 14. Unsurprisingly, the highest deceleration rates are found in the first quarter of the loop ramps. These data are largely consistent with the data from Table 6, showing less deceleration for the second and third quarter of the ramp and then often some acceleration (with higher variability) on the fourth quarter of the ramp.

Table 14. Average Deceleration Rate on Exit Ramps by Ramp Quarter

Exit Ramp	Min Radius (ft)	Fwy SL (mph)	Adv Speed (mph)	Q1 Decel (ft/sec^2)	Q2 Decel (ft/sec^2)	Q3 Decel (ft/sec^2)	Q4 Decel (ft/sec^2)
1	140	55	25	-2.35*** (1.81)**	-0.05 (0.78)	-0.14 (0.82)	-0.26 (1.28)
2	150	60	25	-2.09 (0.92)	-0.11 (0.58)	0.57 (0.66)	2.12 (0.84)
3	155	65	25*	-4.88 (1.79)	-1.15 (1.26)	0.86 (0.63)	-0.84 (1.23)
4	190	65	25	-2.22 (1.25)	-0.46 (0.68)	-0.25 (0.74)	1.13 (0.77)
5	190	55	30	-1.03 (0.63)	0.37 (0.48)	-0.85 (0.81)	1.82 (0.80)
6	230	70	25	-2.17 (1.59)	-0.96 (1.34)	0.12 (1.00)	-2.46 (1.84)
7	230	55	25*	-0.34 (0.69)	0.02 (0.42)	-0.84 (1.06)	0.62 (1.34)
8	325	70	25	-0.84 (1.15)	-0.18 (0.45)	0.09 (0.58)	1.25 (0.77)
Average				**-2.00**	**-0.29**	**-0.09**	**0.77**

*Advisory speed not present on ramp, estimated using the Green Book (*6*)

**Standard deviation in parentheses

*** Negative numbers indicate deceleration on the ramp quarter

In addition to finding the average deceleration rates by ramp quarter, the researcher was also interested in finding the range_{15-85} of deceleration rates. The 85th percentile deceleration values reflect more rapid braking and so warrant extra consideration. These values are summarized in Appendix A. An aggregate of the data from all ramps was used to create Figure 15, which shows the 15th percentile, average, and 85th percentile deceleration rates for each ramp quarter for all vehicles.

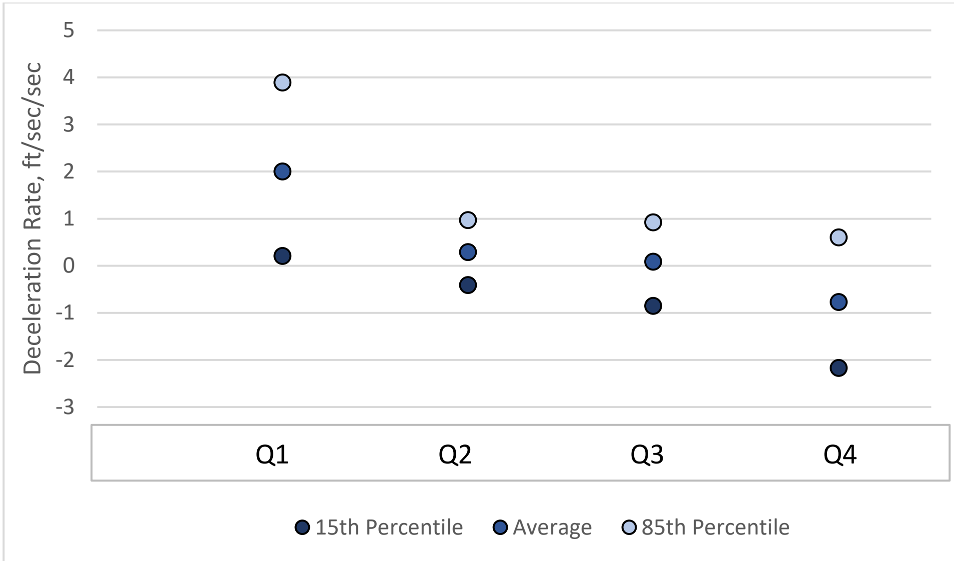


Figure 15. Exit ramp deceleration rates by ramp quarter.

The researcher also found instantaneous deceleration rates at each quarter point along the ramp. The average deceleration rate at each quarter point is shown in Table 15. These values show vehicles braking hardest at the PC of the curve, but still decelerating at the first quarter point. Additionally, the variation in vehicles' braking behavior at the PT becomes much more apparent, with the average vehicle on a two of the signalized ramps decelerating more than 4.0 ft/sec^2 and on many others accelerating more than 2.0 ft/sec^2.

Table 15. Average Instantaneous Deceleration Rates on Exit Ramps

Exit Ramp	Min Radius (ft)	Fwy SL (mph)	Adv Speed (mph)	Vehicle Deceleration by Location (ft/sec^2)				
				PC	**25**	**50**	**75**	**PT**
1	140	55	25	-6.19*** (3.40)**	-1.84 (1.28)	-0.61 (0.79)	-0.19 (2.10)	-0.22 (2.76)
2	150	60	25	-2.93 (1.71)	-0.86 (1.43)	-0.26 (1.04)	1.17 (1.42)	3.03 (1.64)
3	155	65	25*	-4.20 (2.28)	-4.56 (2.22)	-1.35 (1.23)	-0.84 (1.30)	-4.20 (2.41)
4	190	65	25	-2.86 (1.71)	-0.87 (1.13)	0.88 (1.57)	1.80 (1.88)	2.98 (1.76)
5	190	55	30	-2.25 (1.46)	-1.39 (1.30)	-0.92 (1.99)	1.30 (2.29)	2.64 (1.62)
6	230	70	25	-5.48 (3.40)	-3.17 (2.37)	-0.02 (1.12)	-0.44 (1.59)	-5.08 (2.59)
7	230	55	25*	-0.79 (1.12)	-1.14 (1.07)	-0.80 (0.79)	-1.39 (2.53)	2.65 (2.14)
8	325	70	25	-3.82 (2.56)	-1.06 (1.66)	-0.56 (1.59)	0.91 (2.30)	1.90 (1.96)
Average				**-3.56**	**-1.86**	**-0.45**	**0.29**	**0.46**

*Advisory speed not present on ramp, estimated using the Green Book (*6*)

**Standard deviation in parentheses

*** Negative numbers indicate deceleration on the ramp quarter

The researcher then found the range$_{15-85}$ of deceleration values for each exit ramp, shown in Table 16. This table shows that the most variation of vehicle deceleration occurs at the PC of the ramp, where the 85th percentile vehicle on a given ramp decelerates approximately 4.40 ft/sec^2 faster than the 15th percentile vehicle. This broad range shows the need for considering all vehicles on the ramp rather than simply the average vehicle. While the average deceleration rate is only 3.56 ft/sec^2, 15 percent of vehicles decelerate faster than 5.84 ft/sec^2. Additionally, exit ramps 1 and 6 see an 85th percentile PC deceleration rate of around 9.5 ft/sec^2. This value is nearing the value most commonly used for comfortable breaking (10.0 ft/sec^2) and indicates that about 15 percent of vehicles on these ramps are nearing or exceeding this value. No other deceleration values seen on the exit ramps approach this comfortable breaking threshold.

Table 16. Range$_{15-85}$ of Instantaneous Deceleration Rates on Exit Ramps

Exit Ramp	Min Radius (ft)	Fwy SL (mph)	Percen-tile	Vehicle Deceleration by Location (ft/sec^2)				
				PC	25	50	75	PT
1	140	55	15th 85th	-3.03** -9.34	-0.58 -2.87	0.16 -1.49	1.59 -1.6	2.43 -3.65
2	150	60	15th 85th	-1.09 -4.79	0.39 -1.87	0.82 -1.18	2.43 -0.28	4.26 1.64
3	155	65	15th 85th	-1.91 -6.59	-2.05 -7.10	0.00 -2.62	0.48 -2.15	-1.31 -6.63
4	190	65	15th 85th	-1.01 -4.86	0.04 -1.80	2.52 -0.75	3.46 0.00	4.48 1.40
5	190	55	15th 85th	-0.84 -4.02	-0.27 -2.27	1.15 -3.02	3.61 -0.97	4.11 1.18
6	230	70	15th 85th	-2.03 -9.52	-0.07 -6.21	1.35 -0.98	1.33 -1.54	-2.01 -7.92
7	230	55	15th 85th	0.14 -1.74	-0.15 -2.18	-0.19 -1.59	0.53 -4.11	4.61 0.93
8	325	70	15th 85th	-1.53 -5.88	-0.09 -1.89	0.37 -1.40	2.80 -0.75	3.55 0.75
Average			**15th 85th**	**-1.45 -5.84**	**-0.35 -3.27**	**0.77 -1.63**	**2.03 -1.42**	**2.52 -1.54**

** Negative numbers indicate deceleration on the ramp quarter

One of the underlying assumptions in past literature was that acceleration and deceleration occur in a constant fashion along a ramp. The results from the exit loop ramps give reason to question this underlying assumption. The deceleration on these ramps is certainly not constant, but is strongly weighted toward the beginning of the ramp. By directly comparing the instantaneous acceleration rates at the ramp quarter points with the average acceleration rates over the ramp quarters, it can be noted that the average of two consecutive instantaneous acceleration rates tends to be higher than the actual average acceleration rates seen on the ramp. This shows that the derivative of acceleration, jerk, may not even be constant and demonstrates the need to update the assumption of constant deceleration. Table 17 highlights the differences between the 85th percentile instantaneous deceleration at the ramp points and the 85th percentile deceleration over the ramp quarters. This table shows that the most severe deceleration rates are higher at points than they are over distances and suggests that there is not a linear decrease in deceleration from the ramp PC to the first quarter point.

Table 17. 85th Percentile Deceleration Rate by Location on Exit Ramps

Exit Ramp	Ramp Location								
	PC^A	Q1^B	25^A	Q2^B	50^A	Q3^B	75^A	Q4^B	PT^A
1	-9.34	-3.97	-2.87	-0.47	-1.49	-0.83	-1.60	-1.70	-3.65
2	-4.79	-2.94	-1.87	-0.68	-1.18	-0.15	-0.28	1.11	1.64
3	-6.59	-6.41	-7.10	-2.51	-2.62	0.30	-2.15	-2.21	-6.63
4	-4.86	-3.30	-1.80	-1.11	-0.75	-0.93	0.00	0.48	1.40
5	-4.02	-1.63	-2.27	-0.13	-3.02	-1.73	-0.97	1.00	1.18
6	-9.52	-3.52	-6.21	-1.90	-0.98	-0.85	-1.54	-4.52	-7.92
7	-1.74	-1.00	-2.18	-0.38	-1.59	-1.92	-4.11	-0.59	0.93
8	-5.88	-1.64	-1.89	-0.58	-1.40	-0.59	-0.75	0.38	0.75
Average	**-5.84**	**-3.89**	**-3.27**	**-0.97**	**-1.63**	**-0.92**	**-1.42**	**-0.60**	**-1.54**

*A: Instantaneous acceleration rate taken at a ramp quarter point

*B: Average acceleration rate over the ramp quarter; taken by dividing the change in speed between ramp quarter points by the travel time between the two points.

To highlight the variability in the deceleration rate of vehicles, the researcher made histograms for each ramp and each ramp quarter point. These are provided in

Appendix B, and an example is shown in Figure 16. Each bin represents an increment of 1.0 ft/sec^2. This figure shows that vehicles on this exit ramp have the highest deceleration rates at the ramp PC, followed by the first quarter point. Additionally, the least variability occurs at the center of the ramp, and the most variability occurs at the ramp PC and ramp PT.

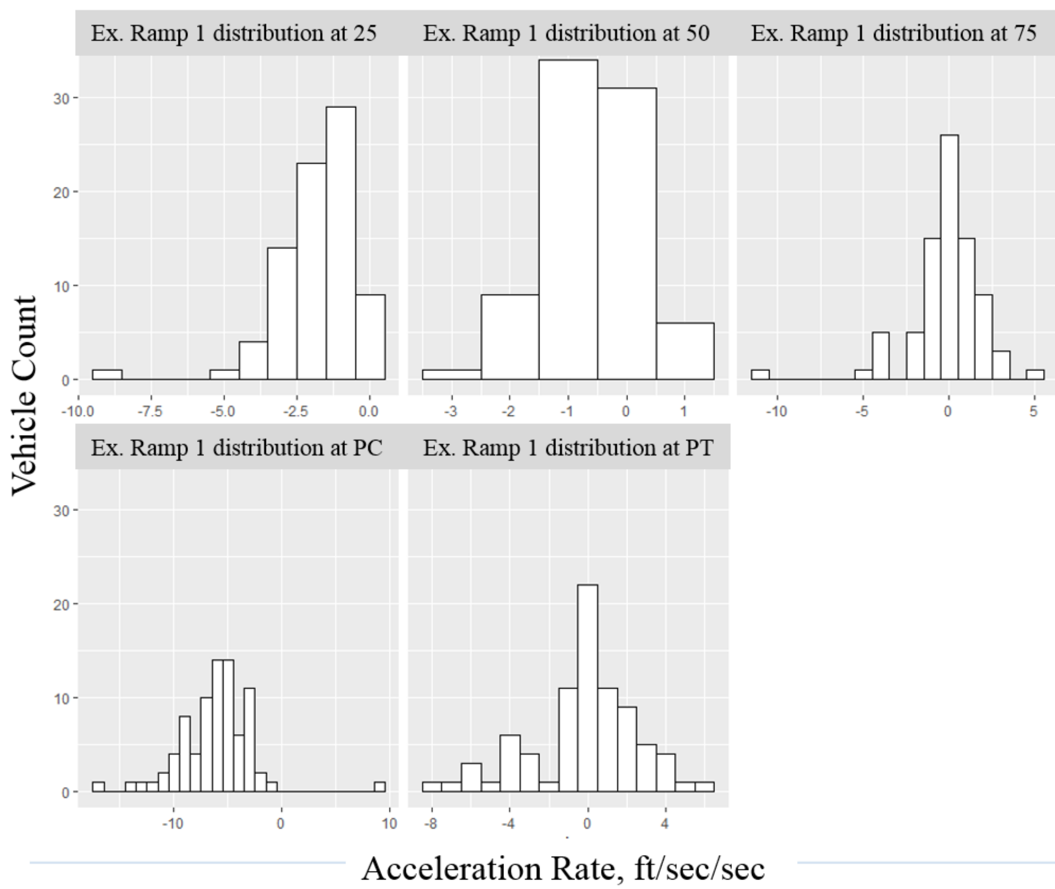


Figure 16. Histograms of acceleration rate on Exit Ramp 1.

Entrance Ramps

To explore acceleration rates on entrance ramps, the researcher first found the average acceleration rates on each ramp quarter. These values are presented in Table 18. Here again, it can be seen that acceleration rates are highest on the last quarter of the ramp.

Table 18. Average Acceleration Rate on Entrance Ramps by Ramp Quarter

Entrance Ramp	Min Radius (ft)	Fwy SL (mph)	Cross-road SL (mph)	Q1 Accel (ft/sec^2)	Q2 Accel (ft/sec^2)	Q3 Accel (ft/sec^2)	Q4 Accel (ft/sec^2)
1	150	55	40	1.41 (0.82)*	-0.75** (0.76)	0.39 (0.51)	1.29 (0.73)
2	160	60	45	-0.96 (1.13)	0.84 (0.60)	-0.69 (0.48)	1.26 (0.70)
3	165	65	45	2.25 (0.93)	-0.27 (0.84)	1.20 (0.93)	2.10 (1.08)
4	175	65	45	0.97 (0.70)	0.69 (0.56)	1.33 (0.76)	2.43 (1.13)
5	175	55	40	0.26 (0.73)	0.48 (0.50)	0.82 (0.63)	1.84 (0.90)
6	185	60	40	0.12 (0.80)	-0.68 (0.66)	1.02 (0.84)	1.75 (1.07)
7	230	70	45	1.55 (0.78)	1.08 (0.71)	1.56 (0.84)	2.27 (1.06)
8	320	70	45	-0.15 (0.60)	-0.04 (0.47)	0.79 (0.84)	1.27 (1.32)
Average				**0.68**	**0.17**	**0.80**	**1.78**

*Standard deviation in parentheses

**Negative numbers indicate deceleration

Next, the researcher found the range$_{15-85}$ of acceleration rates for each ramp quarter. The 15th and 85th percentile acceleration rates for each ramp are provided in Appendix A. On each ramp, Q4 has the highest acceleration values, where the 85th percentile acceleration values for Q4 are over 3.0 ft/sec^2 for three of the ramps. While 3.0 ft/sec^2

is below the threshold for comfortable acceleration, this rate is the average rate maintained over the course of Q4 for the 85th percentile vehicles. It is likely that many of these vehicles approached or surpassed an acceleration rate of 3.6 ft/sec^2 at some point on the final ramp quarter. Figure 17 shows the aggregated average, 15th percentile, and 85th percentile acceleration rates by quarter. From this figure, it is clear that much of the acceleration taking place on the ramp proper occurs during the final quarter of the ramp.

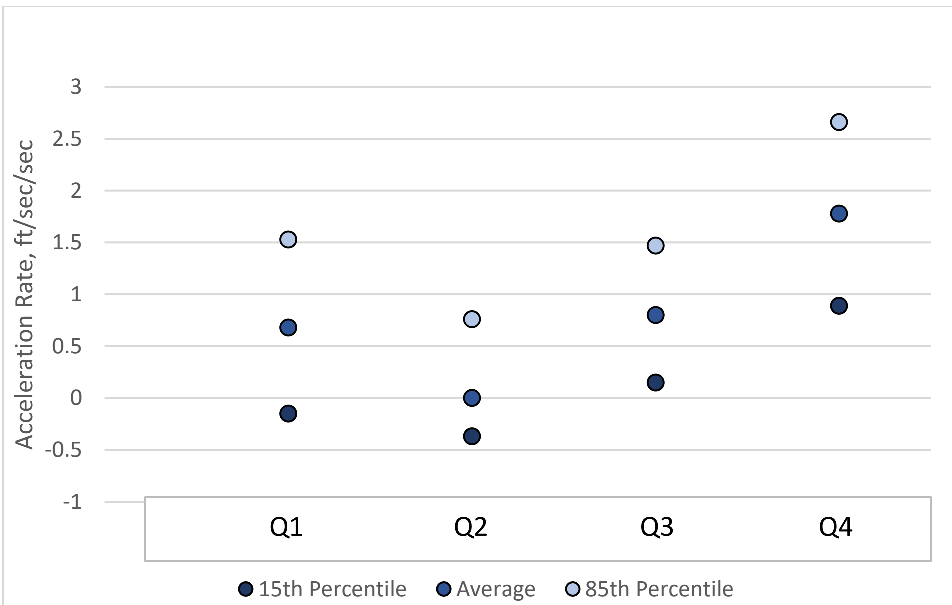


Figure 17. Entrance ramp acceleration rates by quarter.

It is an important consideration that these acceleration rates by ramp quarter are essentially average rates over the length of the ramp quarter. Meaning, the peak acceleration rate experienced by the vehicle on the ramp quarter, assuming variable acceleration, would be higher than the average. For this reason, the researcher thought it valuable to take instantaneous acceleration rates at points along the ramp, anticipating that the average acceleration values, and certainly the 85th percentile acceleration values, would be higher at points.

The researcher found the average acceleration values at each ramp quarter point as well as the range_{15-85} of acceleration values. These values are provided in Table 19 and Table 20, respectively.

Table 19. Average Instantaneous Acceleration Rates on Entrance Ramps

Exit Ramp	Min Radius (ft)	Fwy SL (mph)	Crossroad SL (mph)	Average Vehicle Acceleration by Location (ft/sec^2)				
				PC	**25**	**50**	**75**	**PT**
1	150	55	40	-1.18** (1.76)*	1.27 (1.63)	0.18 (1.30)	1.59 (1.44)	2.75 (1.75)
2	160	60	45	-1.80 (2.44)	0.35 (1.17)	0.53 (1.55)	1.41 (1.02)	3.50 (1.36)
3	165	65	45	3.03 (1.98)	-1.17 (1.71)	-0.30 (1.35)	2.70 (1.67)	3.25 (2.27)
4	175	65	45	3.03 (1.65)	-1.44 (1.22)	-0.85 (0.97)	1.43 (1.66)	2.87 (1.78)
5	175	55	40	-2.15 (1.85)	0.49 (1.17)	-0.66 (0.92)	1.16 (1.36)	3.08 (1.30)
6	185	60	40	2.33 (1.33)	-0.48 (1.23)	1.74 (1.29)	3.37 (1.58)	3.28 (2.43)
7	230	70	45	1.99 (1.35)	0.11 (1.24)	1.22 (1.05)	2.97 (1.05)	2.74 (1.21)
8	320	70	45	0.47 (1.86)	0.29 (1.46)	0.86 (1.56)	1.99 (1.83)	2.25 (1.95)
Average				**0.71**	**-0.07**	**0.34**	**2.08**	**2.96**

*Standard deviation in parentheses

**Negative numbers indicate deceleration

Table 20. Range$_{15-85}$ of Instantaneous Acceleration Rates on Entrance Ramps

Entrance Ramp	Min Radius (ft)	Fwy SL (mph)	Percentile	Vehicle Acceleration Range by Location (ft/sec^2)				
				PC	25	50	75	PT
1	140	55	15th 85th	-2.80** 0.19	-0.49 3.08	-1.13 1.51	0.25 3.17	0.71 4.56
2	150	60	15th 85th	-3.74 -0.37	-0.95 1.41	-1.34 2.26	0.27 2.44	2.17 5.15
3	155	65	15th 85th	1.14 5.25	-3.04 0.34	-1.46 1.05	0.97 4.38	2.55 4.78
4	190	65	15th 85th	1.69 4.95	-2.33 -0.28	-1.87 0.12	-0.43 3.17	0.83 4.72
5	190	55	15th 85th	-4.00 -0.09	-0.75 1.65	-1.68 0.28	-0.24 2.67	1.68 4.50
6	230	70	15th 85th	1.03 3.74	-1.54 0.56	0.37 2.89	1.96 4.67	1.21 5.42
7	230	55	15th 85th	0.47 3.32	-1.03 1.12	0.40 2.05	2.09 4.16	1.77 3.70
8	325	70	15th 85th	-0.93 2.22	-0.56 1.39	0.00 1.90	0.97 3.12	0.92 3.38
Average			**15th** **85th**	**-0.89** **2.40**	**-1.34** **1.16**	**-0.84** **1.51**	**0.73** **3.47**	**1.48** **4.53**

**Negative numbers indicate deceleration

These results show that the average acceleration rate at the PT of the ramp is 2.96 ft/sec^2, with one ramp as high as 3.50 ft/sec^2. Notably, the 85th percentile acceleration rates on many ramps at both the third-quarter point and the PT exceed 4.0 ft/sec^2. In fact, the 85th percentile acceleration rate for the PT of the entrance loop ramps was 4.53 ft/sec^2. This value is considerably higher than the normal acceleration value of 3.6 ft/sec^2 used by the Traffic Engineering Handbook (*10*). This could indicate that either the values used in this handbook are outdated or that many vehicles on these entrance ramps are accelerating at an uncomfortably high rate.

The findings for entrance loop ramps also give reason for questioning the underlying assumption of constant acceleration. Again, the 85th percentile instantaneous acceleration rates are higher while the average acceleration rates over the ramp quarters are more muted. These differences can be more closely examined in Table 21.

Table 21. 85th Percentile Acceleration Rate by Location on Entrance Ramps

Entrance Ramp	Ramp Location								
	PC[A]	**Q1[B]**	**25[A]**	**Q2[B]**	**50[A]**	**Q3[B]**	**75[A]**	**Q4[B]**	**PT[A]**
1	0.19	2.31	3.08	-0.01	1.51	0.80	3.17	1.92	4.56
2	-0.37	0.04	1.41	1.44	2.26	-0.12	2.44	2.00	5.15
3	5.25	3.09	0.34	0.42	1.05	1.98	4.38	3.10	4.78
4	4.95	1.68	-0.28	1.20	0.12	2.02	3.17	3.45	4.72
5	-0.09	1.07	1.65	1.07	0.28	1.39	2.67	2.68	4.50
6	3.74	1.03	0.56	0.00	2.89	1.71	4.67	2.62	5.42
7	3.32	2.37	1.12	1.66	2.05	2.45	4.16	3.04	3.70
8	2.22	0.64	1.39	0.43	1.90	1.50	3.12	2.46	3.38
Average	**2.40**	**1.53**	**1.16**	**0.76**	**1.51**	**1.47**	**3.47**	**2.66**	**4.53**

*A: Instantaneous acceleration rate taken at a ramp quarter point

*B: Average acceleration rate over the ramp quarter; taken by dividing the change in speed between ramp quarter points by the travel time between the two points.

The researcher also made histograms of the instantaneous acceleration rates at each ramp quarter point for each entrance ramp. These are provided in Appendix C and shed light on the variability of acceleration rates on freeway entrance loop ramps. An example of the histograms for Entrance Ramp 1 is provided in Figure 18. Unsurprisingly, this figure shows that the highest acceleration rates occur on the ramp PT and at the third quarter point. It also shows that acceleration rates higher than 4.5 ft/sec^2 are not uncommon at the PT of this ramp.

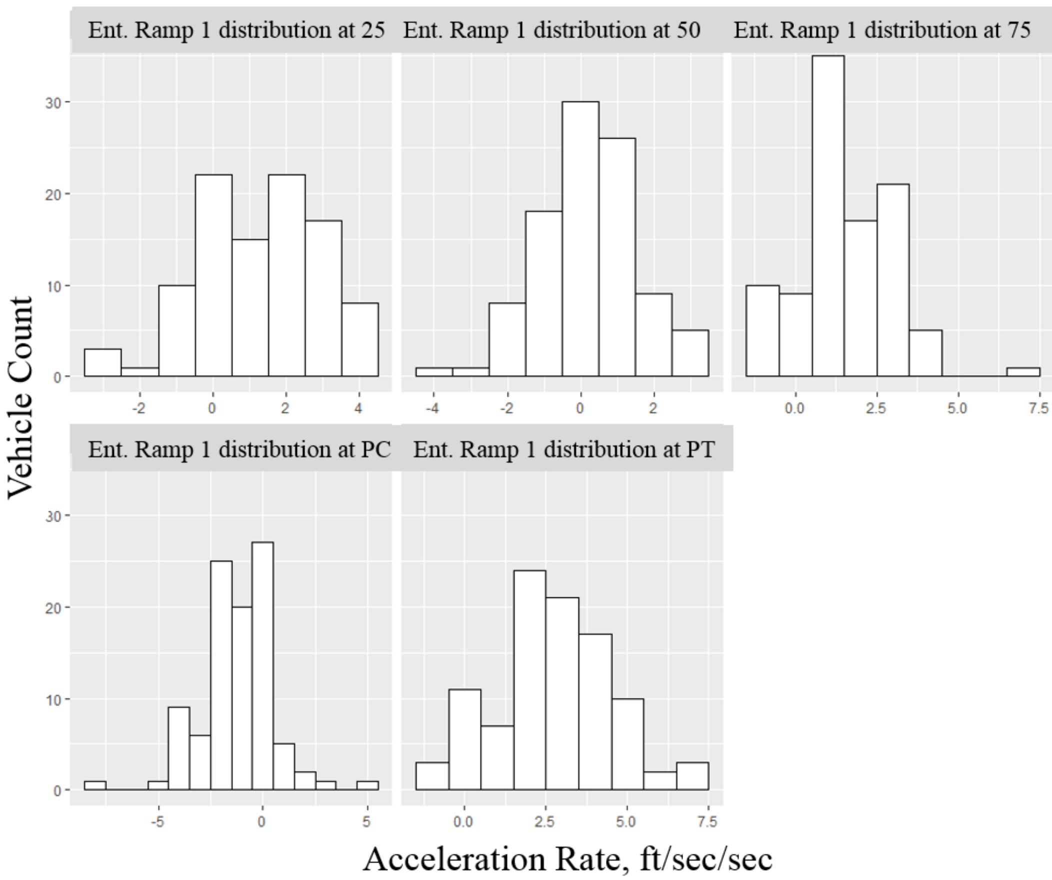


Figure 18. Histograms of acceleration rate on Entrance Ramp 1.

CHAPTER V

APPLICATION OF FINDINGS

Models

The first measure the researcher took to apply the results was to make models that could be used to predict the location and rates of speed change. The researcher built these models to predict the average and the 85th percentile values of acceleration on loop ramps given the most critical ramp characteristics. Because of this, the researcher included eight values to build each model—one for each ramp. Many variables were examined for significance, including radius of curve, freeway speed limit, ramp width and vehicle class. Despite the wealth of variables, two variables proved to be the most predictive for forming models: the radius of the ramp and the freeway speed limit. The researcher thought that vehicle classification might have some small effect, but did not find one, as shown in Appendices D and E. One possible reason is that the vehicle categories are broad, containing vehicles of various performance levels. Additionally, as much of the speed-changing behavior on these loop ramps occurs inside of the extreme values, the performance of the vehicle matters less.

Exit Ramps

The researcher recognized the wide range of deceleration ratio on each ramp segment and searched for ramp variables predictive of deceleration ratio. In doing this, the researcher was primarily concerned with the freeway and Q1 deceleration ratios, as these segments are where most deceleration occurs. Although many ramp variables were analyzed, including lane width and auxiliary lane length, the two variables found to be most predictive of deceleration ratio were the radius of the ramp and the freeway speed. More specifically, as some of the ramps were compound, with radii that were not constant, the freeway speed and the radius of the following ramp quarter were used. For the freeway and auxiliary lane section, this would be the radius of Q1, while for Q1, it would be the radius of Q2. While ramp width did have an impact, the results were counterintuitive, with an increase of lane width resulting in higher deceleration rates, and led to lower adjusted R-square values. It is possible that the direction of causation goes the other way, with the segments requiring more deceleration having wider lanes. Moreover, the radii and ramp width were negatively correlated, so as the radius increased, the ramp width lessened. This is consistent with the viewpoint that ramp width is not as predictive of vehicle deceleration. Additionally, the length of the auxiliary lane was not found to be helpful for the models. Statistical analysis for models both with and without lane width and auxiliary lane length are provided in Appendix D.

The following regression equations were made to predict the average and 85th freeway and Q1 deceleration ratios:

$$DR_{fwy,ave} = 0.0147v_{fwy} - 56.0RadQ1^2 \tag{5}$$

$$DR_{Q1,ave} = 0.0044v_{fwy} - 71.4RadQ2^2 \tag{6}$$

$$DR_{fwy,85} = 0.0168v_{fwy} - 56.9RadQ1^2 \tag{7}$$

$$DR_{Q1,85} = 0.0062v_{fwy} - 86.8RadQ2^2 \tag{8}$$

Where: DR = deceleration ratio, decimal;

v_{fwy} = freeway speed limit, mph; and

RadQn = radius of curve for the n^{th} ramp quarter, miles.

Information on the statistical analysis for these models is provided in Appendix D. While all models are significant at $p<0.01$, the models were marginally better at predicting freeway deceleration ratio than Q1 deceleration ratio. The ramp models for average speed and 85^{th} percentile speed are similar for both freeway deceleration ratio as well as for Q1 deceleration ratio.

As an extreme application of Equation 5, if a freeway had a posted speed limit of 70 mph and Q1 of an exit ramp had a small radius of 150 ft (0.0284 miles), the model predicts a deceleration ratio of 98.4 percent for the freeway and auxiliary lanes. On the other hand, if there is a posted freeway speed limit of 55 mph and a Q1 radius of 500 ft (0.0947 miles), the model predicts that only 30.6 percent of the necessary deceleration should occur on the freeway. All of the ramps under analysis fall within this range. By using the radius-squared term, this model is limited to use within this range but could be quite helpful for such ramps.

Each of these equations indicate that the deceleration ratio on the freeway and Q1 segments increase with a higher freeway speed and decrease when the radius of curve of the following segment is lower. The effect of freeway speed is a logical outcome, as vehicles traveling with a higher initial velocity have more need for deceleration. The effect of radius is also logical, as it indicates that drivers will slow down more when there is a tighter upcoming curve.

Next, the researcher wanted to develop models do predict values of deceleration on exit loop ramps. To achieve this, the researcher developed models that calculate the average and 85th percentile deceleration rate at both the PC of the ramp and at the end of the first quarter. These models are as follows:

$$\alpha_{PC,ave} = -0.051v_{fwy} - 45.4RadQ1 + 64.6RadQ2 \tag{9}$$

$$\alpha_{25,ave} = -0.011v_{fwy} - 51.9RadQ1 + 55.6RadQ2 \tag{10}$$

$$\alpha_{PC,85} = -0.079v_{fwy} - 72.8RadQ1 + 96.7RadQ2 \tag{11}$$

$$\alpha_{25,85} = -0.020v_{fwy} - 81.3RadQ1 + 83.3RadQ2 \tag{12}$$

Where: α = acceleration rate, ft/sec^2;

v_{fwy} = speed limit of freeway, mph; and

RadQn = radius of ramp quarter n, miles.

In general, these models, whose statistical analyses are shown in Appendix D, indicate that vehicles will be breaking harder at the ramp's PC than at the first quarter point, and that the radii of the loops matters. If, for example, the radii of the second ramp quarter is smaller than the ramp radii of the first quarter (a common occurrence with compound ramps), these models indicate that the driver should be braking more at the first quarter point than if the radii were equal. In this situation, the radii being equal would likely indicate a smaller Q1 radius than is typical. In this case, the vehicle would likely have decelerated more ahead of the ramp's PC.

Entrance Ramps

For entrance ramps, the researcher elected to construct models that predict the average and 85th percentile speed differentials for the final two ramp segments—ramp Q4 and the freeway/auxiliary lane section. The findings showed that the most significant variables for determining the speed differentials were the freeway speed limit and the radius of ramp Q4. Again, the researcher considered other variables such as lane width and auxiliary lane length but found that the models were not aided by their inclusion. Appendix E contains models that include only radius and freeway speed limit, as well as models that include these two variables plus either lane width or auxiliary lane length. The models are as follows:

$$SD_{fwy,ave} = 0.461 v_{fwy} - 88.2 RadQ4 \quad (13)$$

$$SD_{Q4,ave} = 0.068 v_{fwy} + 15.0 RadQ4 \quad (14)$$

$$SD_{fwy,85} = 0.533 v_{fwy} - 85.7 RadQ4 \quad (15)$$

$$SD_{Q4,85} = 0.101 v_{fwy} + 23.0 RadQ4 \quad (16)$$

Where: SD = speed differential from beginning of segment to end, mph;

v_{fwy} = freeway speed limit, mph; and

RadQ4 = radius of curve for the 4th ramp quarter, miles.

Details on the statistical analysis for these models is provided in Appendix E. As the data would indicate, these models show that the speed differential on the freeway is expected to be quite a bit larger than the speed differential experienced from the beginning of Q4 to the ramp's PT. The models also show, perhaps intuitively, that a larger radius on the fourth quarter of the ramp leads to a larger speed differential on Q4, as vehicles are able to accelerate more. Importantly, a larger Q4 radius also leads to a lower expected speed differential on the freeway, presumably as vehicles were able to perform some of their necessary acceleration on ramp Q4.

Finally, the researcher developed regression models to predict average and 85th percentile vehicle acceleration at the final two quarter points of the ramp—the third quarter point and the ramp PT. These locations saw the highest speeds and the highest acceleration values. By far, the most important factor in determining vehicle acceleration rate at these points along the ramp was the freeway speed limit. In fact, with the freeway speed limit as the only parameter, the following models could be made:

$$\alpha_{PT,ave} = 0.047 v_{fwy} \tag{17}$$

$$\alpha_{75,ave} = 0.033 v_{fwy} \tag{18}$$

$$\alpha_{PT,85} = 0.071 v_{fwy} \tag{19}$$

$$\alpha_{75,85} = 0.056 v_{fwy} \tag{20}$$

Where: α = acceleration rate, ft/sec^2; and

v_{fwy} = speed limit of freeway, mph.

Each of these models is significant at $p<0.001$. See Appendix E for more details on the statistical analysis of these models. These models indicate that for freeway loop ramps with radii in the studied range of 140-320 feet, the acceleration at the end of the ramp is directly related to the freeway speed limit, or the vehicle's target speed. This is consistent with the idea that vehicles departing a loop ramp can only travel so fast (about 40 mph on the studied ramps), so the demand for acceleration will be highly correlated with the target speed. Equation 19 indicates that 15 percent of vehicles entering a freeway with a speed limit of 70 mph will have an acceleration rate of over 5.0 ft/sec^2 at the PT of the curve. This result further strengthens the finding that many vehicles on freeway loop ramps are forced to accelerate more rapidly than the comfortable acceleration rate of 3.6 ft/sec^2.

Conclusions

As shown in Appendices D and E, each model provided is significant at $p=0.01$ or better. These models are intended to provide a useful tool to estimate the average and 85th percentile acceleration rates on freeway loop ramps at the points that experience the most acceleration. Other predictive models were possible, such as models that use each trip as input rather than one value for each ramp or weighted regression models. As the variance between ramps was not too large, weighted regression models provided similar results to the unweighted models used in this thesis. By including the

85^{th} percentile models, the researcher provides a way to model the more extreme acceleration rates in a simpler manner.

Updating Acceleration Assumptions

The "normal" deceleration and acceleration rates in literature are 10.0 ft/sec^2 and 3.6 ft/sec^2, respectively. However, the researcher noted that these values may not be appropriate for use on freeway loops. The average instantaneous deceleration rate at the exit ramp PT was only 3.56 ft/sec^2 while the 85^{th} percentile deceleration rate only approached 10.0 ft/sec^2 on two of the eight ramps. On the other hand, the average acceleration at the PT on entrance loop ramps was 2.96 ft/sec^2 while the 85^{th} percentile acceleration rates were commonly over 4.5 ft/sec^2. This indicates that on loop ramps, the acceleration and deceleration values may be closer than previously thought. To explore this possibility, the researcher combined Figure 13 and Figure 14 to examine the speed profiles on entrance and exit ramps together. To do this, the entrance ramps were flipped so that vehicle speed could be directly compared at each ramp quarter point. The results of this process can be seen in Figure 19 and Figure 20, which show the individual ramp speeds at each location and the aggregated ramp speeds, respectively. In these figures, the nearest QP refers to the ramp quarter point nearest the freeway and the fifth QP refers to the ramp quarter point nearest the crossroad.

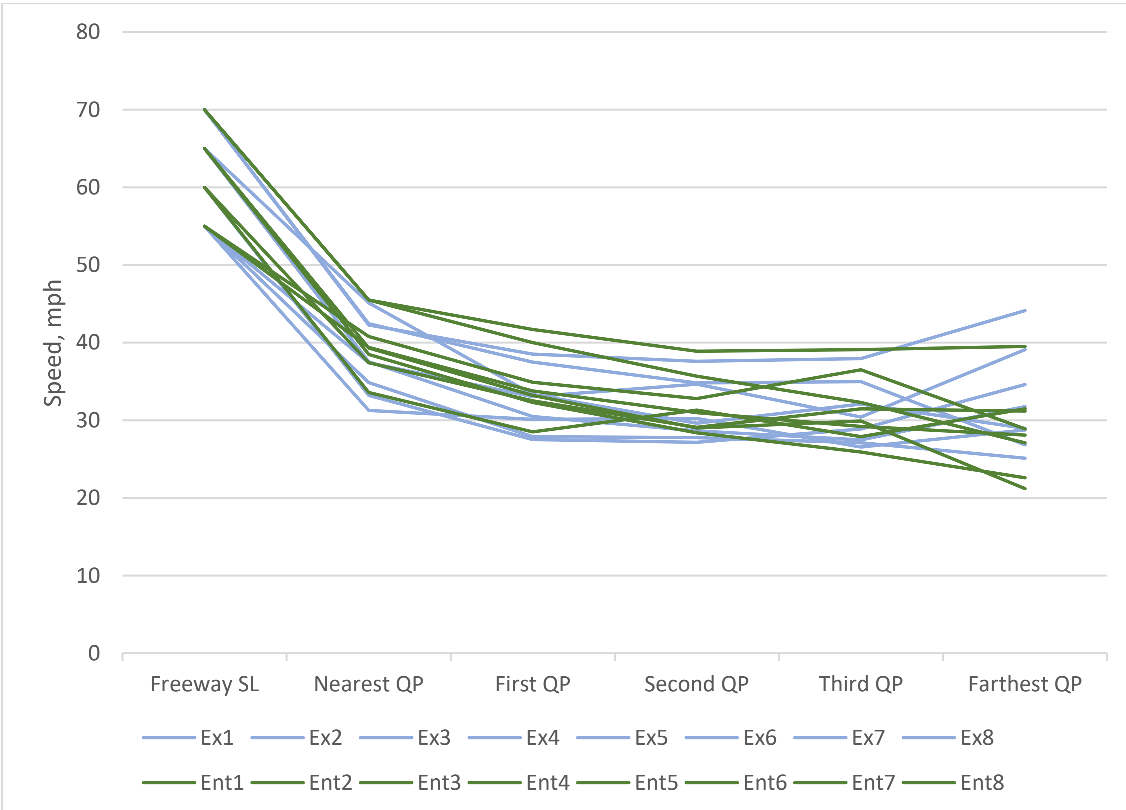


Figure 19. Comparison of speed on entrance and exit loop ramps.

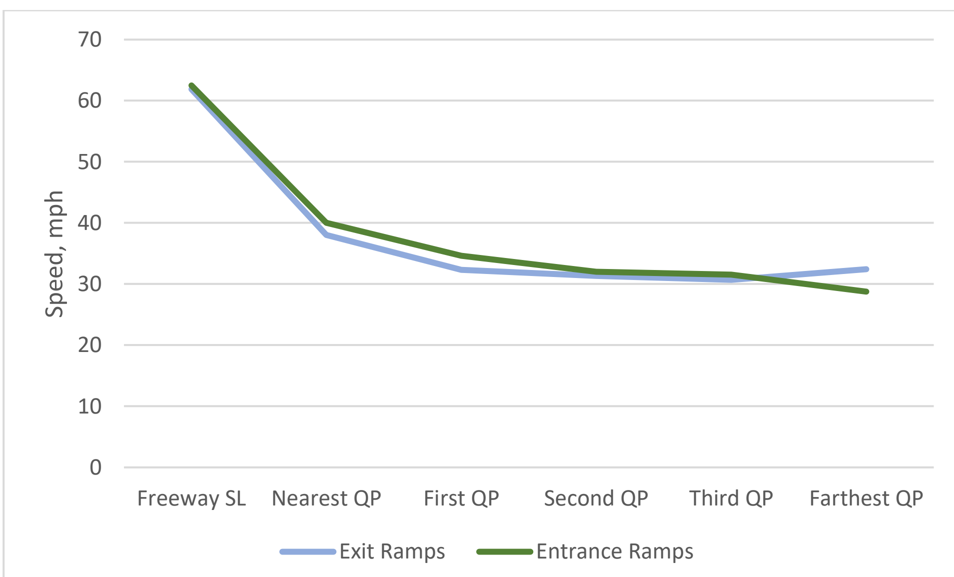


Figure 20. Aggregate comparison of speed on entrance and exit loop ramps.

Although there is some variance between ramps, these figures show that vehicle speed on entrance loop ramps largely mirrors vehicle speed on exit loop ramps. To study this further, the researcher applied the same process to vehicle acceleration rates on these ramps. Figure 21 and Figure 22 show the acceleration rate by ramp and the aggregate acceleration rate, respectively. In Figure 21, the ramps that begin or terminate at a signal are shown in dashed lines while ramps that are free-flowing at the crossroad are shown as solid. There is a strong divergence in acceleration rates at the fifth quarter point depending on the crossroad traffic control.

These figures show that acceleration on entrance loop ramps largely mirrors deceleration on exit loop ramps. This finding could indicate the need to lower the assumed deceleration rate on exit loop ramps to more closely match the assumed acceleration rate on entrance loop ramps.

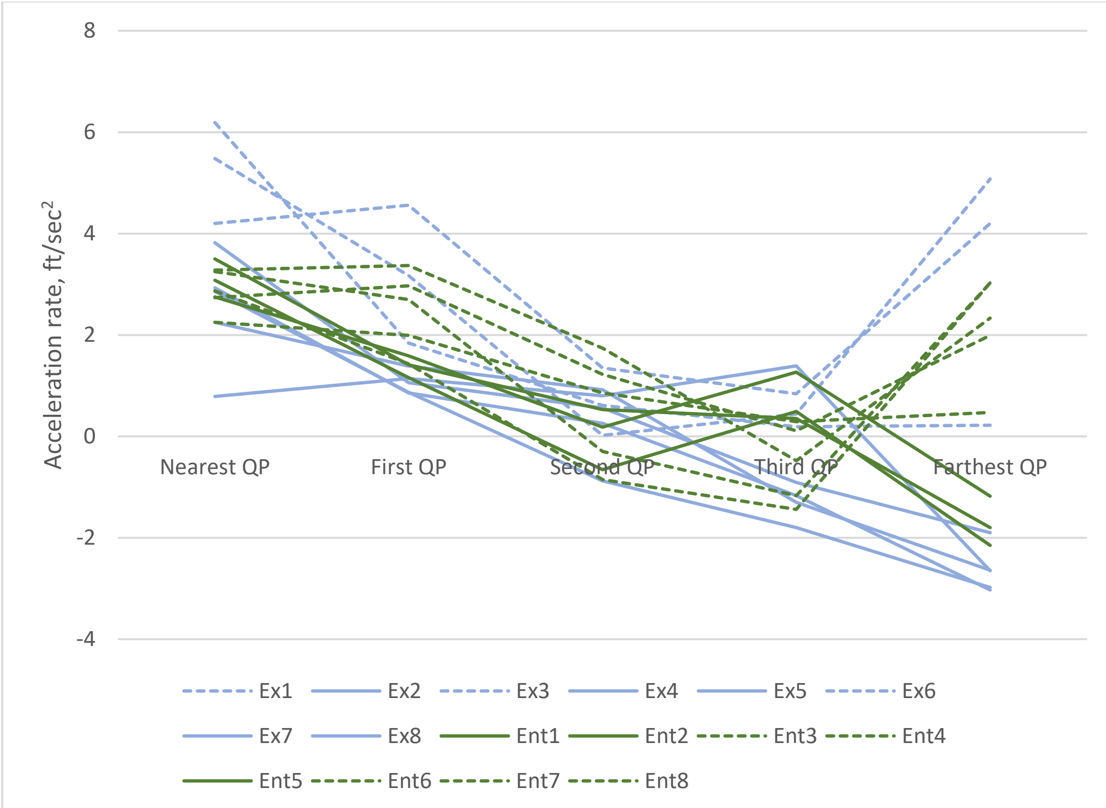


Figure 21. Comparison of acceleration rates on entrance and exit loop ramps.

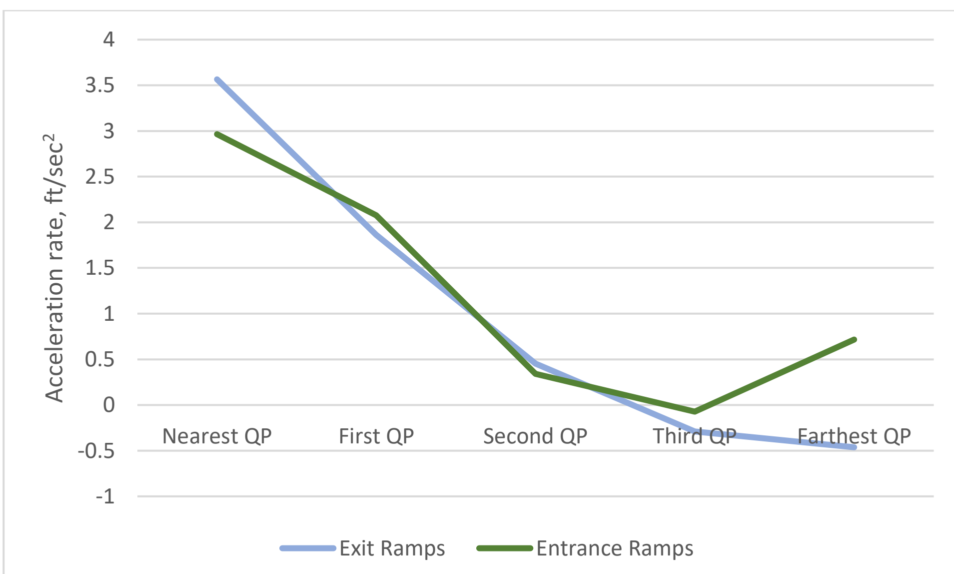


Figure 22. Aggregate comparison of acceleration rates on entrance and exit loop ramps.

Auxiliary Lane Application

The findings from this research reiterate the necessity of auxiliary lanes. Across entrance loop ramps, the average vehicle speed when crossing the ramp PT was only 40 mph, while fifteen percent of vehicles passed the PT traveling less than 35.4 mph. These vehicles will accelerate and eventually reach freeway speed, and they will have to perform that acceleration on the freeway if no auxiliary lane is present. On exit loop ramps, the average vehicle reaches the ramp PC traveling 38.0 mph and fifteen percent of vehicles travel less than 33.3 mph.

The data from this effort can be used for determining the minimum length of auxiliary lane necessary to encourage speed changing either before merging into the freeway mainlines or after departing them.

Exit Ramps

Once the researcher has estimated the freeway deceleration ratio for an exit loop ramp using Equations 5 through 8, the following formula can be used to determine the necessary length of deceleration lane:

$$L_{dec} = v_{ave} * 1.47 * \left(\frac{1.47 * (v_{fwy} - v_{target}) * DR_{fwy}}{\alpha}\right) \tag{21}$$

Where: L_{dec} = Length of deceleration lane, ft;

v_{fwy} = Freeway speed limit, mph;

v_{target} = Assumed ramp speed, mph;

v_{ave} = Average of freeway speed and target speed, mph;

DR_{fwy} = Expected deceleration ratio occurring before the ramp PC, percent;

α = Deceleration rate, ft/sec^2.

Although the comfortable deceleration rate of 10.0 ft/sec^2 can be used for the deceleration rate in the formula, the vehicle data indicate that this value is likely higher than the actual deceleration rates of vehicles at the ramp PC. If a lower value is used, the recommended length of deceleration will increase accordingly. Using a lower deceleration rate would also ensure that more vehicles have time to slow down.

For an application of this model, if freeway has a speed limit of 65 mph, the advisory or target speed of the ramp proper is 30 mph, and the expected freeway deceleration ratio was four-fifths, the recommended minimum deceleration lane length would be 290 ft. Table 22 shows the minimum deceleration lane length necessary for vehicles when different deceleration rates are assumed. In other studies, it has been assumed that vehicles will coast for some time before

Table 22. Minimum Recommended Deceleration Lane Length by Deceleration Rate

v_{fwy} (mph)	v_{target} (mph)	DS_{fwy}	L_{dec} (ft) Dec = 10.0 ft/sec^2	L_{dec} (ft) Dec = 8.0 ft/sec^2	L_{dec} (ft) Dec = 6.0 ft/sec^2
55	25	80%	210	260	350
55	30	80%	185	230	310
55	35	80%	160	295	260
60	25	80%	260	325	430
60	30	80%	235	295	390
60	35	80%	210	260	345
65	25	80%	315	390	520
65	30	80%	290	360	480
65	35	80%	260	325	435
70	25	80%	370	465	620
70	30	80%	350	435	580
70	35	80%	320	400	530
75	25	80%	435	540	720
75	30	80%	410	515	685
75	35	80%	385	475	635
55	25	67%	175	220	290
55	30	67%	155	195	260
55	35	67%	135	165	220
60	25	67%	220	270	360
60	30	67%	200	245	330
60	35	67%	175	215	290
65	25	67%	265	330	435
65	30	67%	245	305	405
65	35	67%	220	275	365
70	25	67%	310	390	525
70	30	67%	290	365	485
70	35	67%	270	335	445
75	25	67%	365	454	605
75	30	67%	345	430	570
75	35	67%	320	400	535

applying the brake pedal. For this research, details were not available on the freeway for the duration that this type of deceleration might occur. For this reason, constant deceleration is assumed for this model, although as the findings from this paper indicate, this might not be an accurate assumption.

The author evaluated the adequacy of the existing freeway deceleration lanes from the studied exit loop ramps using a deceleration rate of 6.0 ft/sec^2. The results from this process can be seen in Table 23. All five of the six ramps with deceleration lanes were roughly adequate for at least 85 percent of vehicles. The researcher also used the higher deceleration rate values of 8.0 ft/sec^2 and 10.0 ft/sec^2, the "normal" deceleration rate. These values are shown in Table 24. As the auxiliary lanes were mostly adequate using the assumed deceleration rate of 6.0 ft/sec^2, the ramps held up even better under the assumption of higher deceleration rates. This could indicate that the 10.0 ft/sec^2 is too high of an assumed deceleration rate for exiting vehicles, a lower assumed deceleration rate, such as 6.0 ft/sec^2 may be more applicable.

Table 23. Test for Deceleration Lane Adequacy on Studied Ramps

Entrance Ramp	v_{fwy} (mph)	v_{target} (mph)	Radius Q1 (ft)	$DS_{fwy,Ave}$ (percent)	$DS_{fwy,85}$ (percent)	L_{actual} (ft)	$L_{min,ave}$ (ft)	$L_{min,85}$ (ft)
1	55	25	330	67.1%	83.0%	475	290	360
2	60	25	150	76.5%	86.2%	0	410	465
3	65	25*	450	49.7%	62.1%	375	325	405
4	65	25	370	68.6%	80.1%	550	445	520
5	55	30	415	70.4%	84.5%	730	270	325
6	70	25	480	61.2%	72.4%	0	475	560
7	55	25*	255	79.1%	87.9%	535	345	380
8	70	25	380	61.6%	76.0%	575	475	585

*Advisory speed not present on ramp, estimated using the Green Book (*6*)

Table 24. Test for Deceleration Lane Adequacy on Studied Ramps for Various Deceleration Rates

Entrance Ramp	L_{actual} (ft)	Deceleration = 10.0 ft/sec^2		Deceleration = 8.0 ft/sec^2		Deceleration = 6.0 ft/sec^2	
		$L_{min,ave}$ (ft)	$L_{min,85}$ (ft)	$L_{min,ave}$ (ft)	$L_{min,85}$ (ft)	$L_{min,ave}$ (ft)	$L_{min,85}$ (ft)
1	475	175	215	220	270	290	360
2	0	250	280	310	350	410	465
3	375	195	245	245	305	325	405
4	550	270	315	335	390	445	520
5	730	165	195	205	245	270	325
6	0	285	335	355	420	475	560
7	535	205	230	260	285	345	380
8	575	284	355	360	440	475	585

Entrance Ramps

The necessary length for acceleration lanes for freeway entrance loop ramps can be calculated similarly, using the speed differential between the vehicle at the ramp PT and the freeway speed limit, as follows:

$$L_{acc} = v_{ave} * 1.47 * \left(\frac{1.47 * SD_{fwy}}{\alpha}\right) \tag{22}$$

Where: L_{acc} = Length of acceleration lane, ft;

v_{ave} = Average of freeway speed and vehicle speed at the ramp PT, mph;

SD_{fwy} = Expected speed differential between the freeway speed and the vehicle speed at the ramp PT, mph; and

α = Acceleration rate, ft/sec^2.

To make these calculations, the researcher used the normal acceleration rate of 3.6 ft/sec^2 (*10*), as well as the acceleration rate recommend by Fitzpatrick and Zimmerman (*2*) of 2.5 ft/sec^2. Consistent with Fitzpatrick and Zimmerman, who note that constant acceleration may be reasonable to use for vehicles entering a freeway on an auxiliary lane, constant acceleration is used for these equations. However, as this paper has suggested, there may be a need to revisit this assumption. The resulting recommended lengths are shown in Table 25.

Table 25. Minimum Recommended Acceleration Lane Length by Acceleration Rate

v_{fwy} (mph)	v_{PT} (mph)	SD_{fwy}	L_{acc} (ft) Acc = 2.5 ft/sec^2	L_{acc} (ft) Acc = 3.6 ft/sec^2
55	35	20	780	540
55	30	25	920	640
55	25	30	1040	720
60	40	20	865	600
60	35	25	1030	715
60	30	30	1165	810
65	45	20	955	660
65	40	25	1135	790
65	35	30	1300	900
70	50	20	1040	720
70	45	25	1245	865
70	40	30	1430	990
75	55	20	1125	870
75	50	25	1355	640
75	45	30	1560	1080

The necessary acceleration lane lengths are noticeably larger than the necessary deceleration lane lengths, due in large part to the lower acceleration rates. Although the researcher for this thesis avoided studying loop ramps with short weaving sections, the space necessary for such long acceleration lanes can be even more problematic, as an entrance loop ramp is often followed in quick succession by an exit loop ramp.

Importantly, these values assume that vehicles will need to accelerate to the freeway speed limit. Realistically, the speed a vehicle needs to achieve may be either higher or lower than the actual speed limit. In heavier traffic, when there are the fewest opportunities to merge with the freeway traffic, it is possible that the vehicle does not need to accelerate all the way up to the freeway speed limit. In this case, the minimum acceleration lane lengths would be somewhat shorter.

The researcher applied these formulas to the studied freeway entrance ramps to determine the adequacy of the existing acceleration lanes if an acceleration rate of 3.6 ft/sec^2 was used. The findings are presented in Table 26 and show that two and nearly three of the eight studied ramps are adequate for the average vehicle while only one is adequate for the at least 85 percent of vehicles. If the suggested constant acceleration value of 2.5 ft/sec^2 is used instead, the acceleration lane lengths would appear all the more inadequate. These results help show the need for, and perhaps the difficulty of, having adequate acceleration lanes for vehicles entering a freeway from a loop ramp.

Table 26. Test for Acceleration Lane Adequacy on Studied Ramps

Entrance Ramp	v_{fwy} (mph)	Radius Q4 (ft)	$SD_{fwy,Ave}$ (mph)	$SD_{fwy,85}$ (mph)	L_{actual} (ft)	$L_{min,ave}$ (ft)	$L_{min,85}$ (ft)
1	55	600	14.2	17.8	795	410	495
2	60	165	26.4	29.7	450	665	720
3	65	360	25.7	31.3	0	730	835
4	65	440	26.5	31.8	310	825	940
5	55	450	15.6	19.6	540	540	650
6	60	310	22.6	26.0	585	595	655
7	70	230	24.5	30.2	0	705	815
8	70	460	24.5	30.7	715	850	1010

CHAPTER VI

SUMMARY AND CONCLUSIONS

This thesis had several objectives, but the overall goal was to develop a more thorough understanding of acceleration and deceleration on loop ramps. In the course of the study, the researcher was able to utilize the SHRP2 NDS to obtain data for nearly 1400 complete trips occurring on 16 freeway loop ramps—8 entrance ramps and 8 exit ramps. The researcher was able to show where on freeway loop ramps acceleration and deceleration typically occur. The researcher measured the impact of various geometric design elements on vehicle speed change and found that the radius of the loop ramp was by far the most significant geometric variable. The researcher also found that the speed limit of the freeway was a major factor in determining vehicle acceleration on entrance ramps and deceleration on exit ramps. The researcher then modeled the speed change rate on these facilities based on these characteristics. The acceleration and deceleration values found on these freeway loop ramps were compared to the values used for "normal acceleration" and "comfortable deceleration," finding that deceleration rates were typically under this threshold, while acceleration values were often above.

Findings

A key finding of this thesis was that much of the speed change necessary to transition from a freeway to a loop ramp or vice versa occurs outside of the loop ramp itself, showing the importance of auxiliary lanes. Vehicles will not enter a loop ramp at freeway speed, nor will they exit one at freeway speed. To avoid severe speed differentials on the freeway, auxiliary lanes are necessary. The researcher developed models that could be used to estimate speed change rates and could be used to evaluate if an auxiliary lane length is sufficient to handle necessary speed change.

Exit Ramps

On exit loop ramps, the finding was that, on average across ramps, two-thirds of the vehicle deceleration occurs before the vehicle reaches the exit loop ramp. Looking at individual ramps, the freeway deceleration ratio was as high as four-fifths. Across exit ramps, 15 percent of vehicles experience more than four-fifths of their deceleration before crossing the ramp PC. It was found that the main factors that determined the amount of deceleration occurring before the freeway ramp were the ramp radius and the speed limit of the freeway. The author also found that deceleration rates on freeway exit loop ramps are typically lower than the “normal” deceleration rate of 10.0 ft/sec^2 and suggests using a smaller value, such as 6.0 ft/sec^2.

Generally, these results show the importance of deceleration lanes for traffic exiting on loop ramps. Vehicles need to slow down before reaching the ramp PC, so to avoid deceleration taking place on the freeway mainlines, auxiliary lanes should be used. Although there can be some difficulty providing adequate room for auxiliary lanes for freeway loop ramps, most of the exit ramps examined in this study had adequate deceleration lanes.

Entrance Ramps

For freeway entrance loop ramps, an average of about twice as much acceleration occurs after the ramp PT as occurs on the entirety of the ramp. Across the eight ramps, the average vehicle left the ramp PT at 40.0 mph and needed to increase its speed by 22.5 mph to match the freeway speed limit. Fifteen percent of vehicles crossed the PT traveling under 35.4 mph and fifteen percent needed to speed up by at least 27 mph to reach the speed limit. Although ramp radius was used to model the location of acceleration, the actual acceleration values at the ramp PT could be modeled with just the freeway speed limit.

Clearly, it is not plausible for vehicles to leave a freeway loop ramp at freeway speed. Therefore, it is important that vehicles have an appropriate place to gain speed outside of the freeway mainlines. Auxiliary lanes can and have been used to serve this purpose. Because vehicles are able to slow down more rapidly than they can speed up, providing an acceleration lane of adequate length for an entrance ramp can be a bigger challenge than providing a deceleration lane of adequate length for an exit ramp. In fact, using the constant acceleration rate of 2.5 ft/sec^2 recommend by Fitzpatrick and Zimmerman (*2*), only one of the eight studied ramps had an acceleration lane adequate for the vehicles to reach freeway speed. Using the "normal acceleration" rate from the *Traffic Engineering Handbook* (*10*) of 3.6 ft/sec^2, only three ramps were either adequate or close to being adequate. On the entrance ramps, acceleration rates higher than 3.6 ft/sec^2 were seen quite commonly. On entrance ramps where the acceleration lane is not adequate and there is not space available to increase it, considerations such as alternative interchange designs or a lower freeway speed limit should be made to avoid severe speed differentials between freeway traffic and entering traffic.

Recommendations

Based on the research, the author makes the following recommendations:

- To comfortably accommodate at least 85 percent of exiting vehicles and ensure that too much deceleration does not occur on the freeway, auxiliary lanes before freeway exit loop ramps should be long enough to cover about 80 percent of the deceleration necessary to slow from the freeway speed to the advisory speed of the loop ramp under a deceleration rate of either 6.0 ft/sec^2 or a different value as indicated by future research.
- To comfortably accommodate at least 85 percent of entering vehicles and ensure that too much acceleration does not occur on the freeway, auxiliary lanes after the freeway entrance ramp should be long enough to accommodate vehicles speeding up from 35 mph to either the freeway speed limit or within five miles of the freeway speed limit at a rate of either 3.6 ft/sec^2 or a different value as indicated by future research.

Limitations

The limitations of this thesis are as follows:

- This project was limited to freeway loop ramps attached directly from the crossroad to the freeway mainline. No freeway loop ramps attached to collector-distributor roads were analyzed. It is likely that the nature of speed change is different for vehicles on loop ramps that are entering from or exiting to collector-distributor roads rather than the freeway itself. The sense of urgency and accompanying rates of speed change are likely higher for loop ramps that have no collector-distributor.

- Although this project had data for vehicle trips on the ramp, the dataset did not have data for the vehicle on the freeway, either before the vehicle exited or after it entered. This data could be quite useful to determine, for example, how far after the ramp PT the vehicle stops accelerating on an entrance ramp. For exit loop ramps, this data could also be used to see whether constant deceleration is a valid assumption, and if not, how long vehicles typically decelerate in gear before applying pressure to the brake pedal.
- The data used by the researcher did not have a precise location for each line of data. To combat this, the researcher applied a method of locating the vehicle using the known radius of the ramp. Still, less positional certainty is had this way as opposed to collecting data in field.

Future Research

Given the limitations of this thesis, the author recommends the following for future research:

- Research examining the vehicle dynamics on auxiliary lanes associated with loop ramps and on the freeway sections adjacent to the auxiliary lanes would help gain a complete picture of vehicle dynamics when entering from or exiting onto loop ramps. Specifically, measuring the acceleration and deceleration rates of vehicles on loop ramp auxiliary lanes could be valuable to updating the acceleration rate assumptions of both rate and variability.

- Research that examined acceleration and deceleration on freeway-to-freeway loop ramps could remove some extraneous variables of the crossroad and show the auxiliary lane needs of vehicles that are required to both slow down and speed up.

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APPENDIX A

ADDITIONAL TABLES

Table A-1. Range$_{15-85}$ of Vehicle Speed by Exit Ramp Location

Exit Ramp	Min Radius (ft)	Fwy SL (mph)	Percentile	Vehicle Speed Range by Location (mph)				
				PC Speed	25 Speed	50 Speed	75 Speed	PT Speed
1	140	55	15th 85th	30.1 39.3	25.0 31.6	24.8 30.7	23.3 30.9	16.3 31.8
2	150	60	15th 85th	29.8 37.3	24.5 30.1	24.0 29.5	25.4 31.7	30.9 38.5
3	155	65	15th 85th	37.6 49.3	27.2 36.1	25.0 31.5	27.9 35.0	21.2 33.5
4	190	65	15th 85th	33.0 42.0	27.4 33.7	25.0 32.2	23.5 31.1	28.1 35.4
5	190	55	15th 85th	33.9 41.0	29.8 36.1	31.0 38.2	25.5 35.2	34.3 43.3
6	230	70	15th 85th	37.4 47.1	33.3 41.1	30.8 38.7	31.6 39.1	18.2 30.9
7	230	55	15th 85th	29.2 36.8	29.1 34.8	28.5 35.6	24.6 33.6	24.0 37.1
8	325	70	15th 85th	35.8 50.2	35.1 43.1	33.8 42.2	32.4 43.4	38.9 50.3
Average			**15th 85th**	**33.3 42.9**	**28.9 35.8**	**27.9 34.8**	**26.8 35.0**	**26.5 37.6**

*Advisory speed not present on ramp, estimated using the Green Book (*6*)

Table A-2. Range$_{15-85}$ of Vehicle Speed by Entrance Ramp Location

Entrance Ramp	Min Radius (ft)	Fwy SL (mph)	Percentile	Vehicle Speed Range by Location (mph)				
				PC	25	50	75	PT
1	140	55	15th 85th	24.6 32.3	32.5 39.9	29.0 36.7	31.3 38.5	37.2 44.9
2	150	60	15th 85th	27.2 37.2	25.5 30.1	27.5 35.3	26.0 31.4	30.3 38.0
3	155	65	15th 85th	16.7 24.3	26.1 33.3	25.5 32.2	29.2 37.7	33.7 44.2
4	190	65	15th 85th	20.0 25.6	22.9 30.1	25.9 31.4	29.3 36.1	33.2 43.2
5	190	55	15th 85th	24.0 32.3	26.0 31.2	26.6 35.1	30.0 37.6	35.4 43.7
6	230	70	15th 85th	28.6 33.7	28.8 34.7	26.0 32.3	29.9 36.2	34.0 42.5
7	230	55	15th 85th	23.7 30.4	29.4 35.3	32.3 39.3	35.4 44.2	39.8 50.6
8	325	70	15th 85th	33.8 44.8	35.0 44.6	34.1 45.0	36.6 45.4	39.3 53.2
Average			15th 85th	**24.8** **32.6**	**28.3** **34.9**	**28.4** **35.9**	**31.0** **38.4**	**35.4** **45.0**

Table A-3. Range$_{15-85}$ of Deceleration Rate on Exit Ramps by Ramp Quarter

Ramp	Min Radius (ft)	Fwy SL (mph)	Percen-tile	Q1 Decel (ft/sec^2)	Q2 Decel (ft/sec^2)	Q3 Decel (ft/sec^2)	Q4 Decel (ft/sec^2)
1	140	55	15th 85th	-1.09 -3.97	0.52 -0.47	0.63 -0.83	1.08 -1.70
2	150	60	15th 85th	-1.26 -2.94	0.45 -0.68	1.25 -0.15	2.99 1.11
3	155	65	15th 85th	-3.12 -6.41	0.03 -2.51	1.38 0.30	0.39 -2.21
4	190	65	15th 85th	-1.12 -3.30	0.16 -1.11	0.49 -0.93	1.83 0.48
5	190	55	15th 85th	-0.45 -1.63	0.93 -0.13	-0.05 -1.73	2.71 1.00
6	230	70	15th 85th	-0.85 -3.52	0.32 -1.90	1.05 -0.85	-1.01 -4.52
7	230	55	15th 85th	0.17 -1.00	0.41 -0.38	0.03 -1.92	1.91 -0.59
8	325	70	15th 85th	0.06 -1.64	0.23 -0.58	0.68 -0.59	2.05 0.38
Average			**15th** **85th**	**-0.21** **-3.89**	**0.41** **-0.97**	**0.85** **-0.92**	**2.17** **-0.60**

*Advisory speed not present on ramp, estimated using the Green Book (*6*)

** Negative numbers indicate deceleration on the ramp quarter

Table A-4. Range$_{15-85}$ of Acceleration Rates on Entrance Ramps by Ramp Quarter

Entrance Ramp	Min Radius (ft)	Fwy SL (mph)	Percen-tile	Q1 Accel (ft/sec^2)	Q2 Accel (ft/sec^2)	Q3 Accel (ft/sec^2)	Q4 Accel (ft/sec^2)
1	140	55	15th 85th	0.48 2.31	-1.22 -0.01	-0.08 0.80	0.65 1.92
2	150	60	15th 85th	-2.13 0.04	0.29 1.44	-1.20 -0.12	0.59 2.00
3	155	65	15th 85th	1.42 3.09	-0.74 0.42	0.60 1.98	1.19 3.10
4	190	65	15th 85th	0.32 1.68	0.08 1.20	0.72 2.02	1.28 3.45
5	190	55	15th 85th	-0.52 1.07	0.02 1.07	0.11 1.39	1.15 2.68
6	230	70	15th 85th	-0.68 1.03	-1.28 0.00	0.33 1.71	0.98 2.62
7	230	55	15th 85th	0.81 2.37	0.53 1.66	1.00 2.45	1.60 3.04
8	325	70	15th 85th	-0.88 0.64	-0.61 0.43	-0.26 1.50	-0.30 2.46
Average			**15th** **85th**	**-0.15** **1.53**	**-0.37** **0.76**	**0.15** **1.47**	**0.89** **2.66**

**Negative numbers indicate deceleration

APPENDIX B

ACCELERATION HISTOGRAMS FOR EACH EXIT RAMP

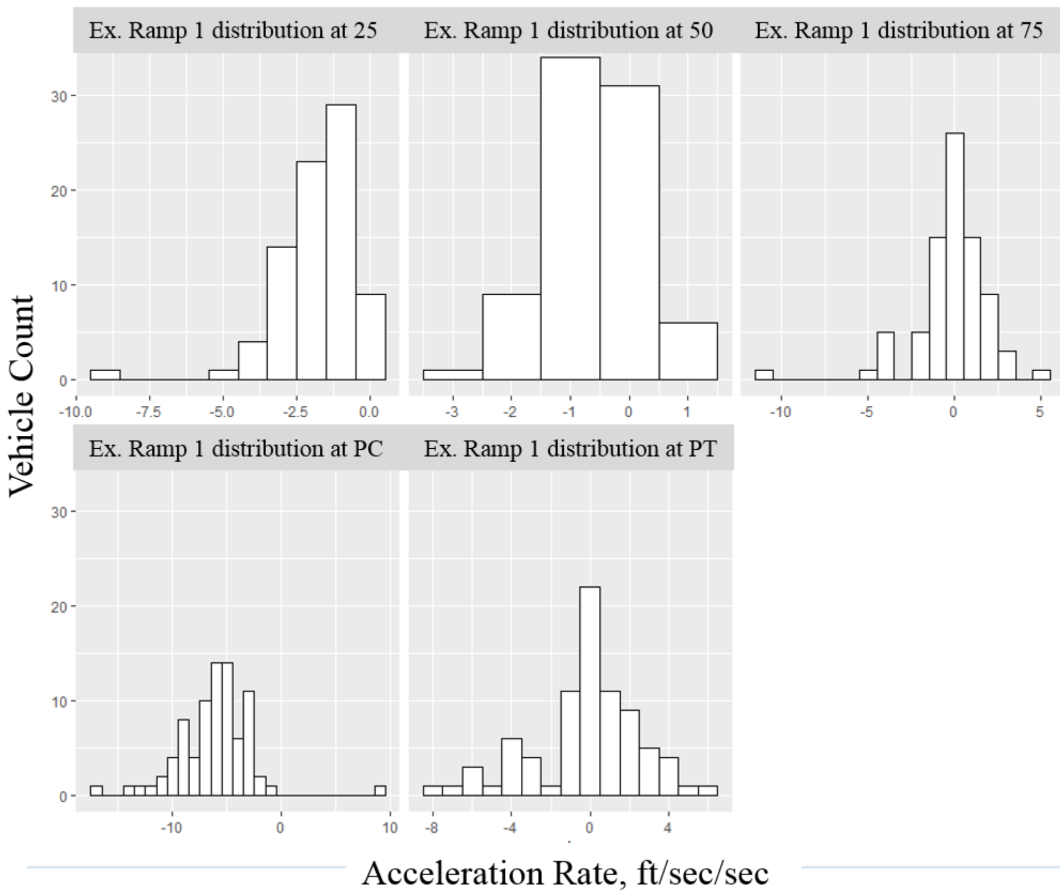

Figure B-1. Histograms of acceleration rate on Exit Ramp 1.

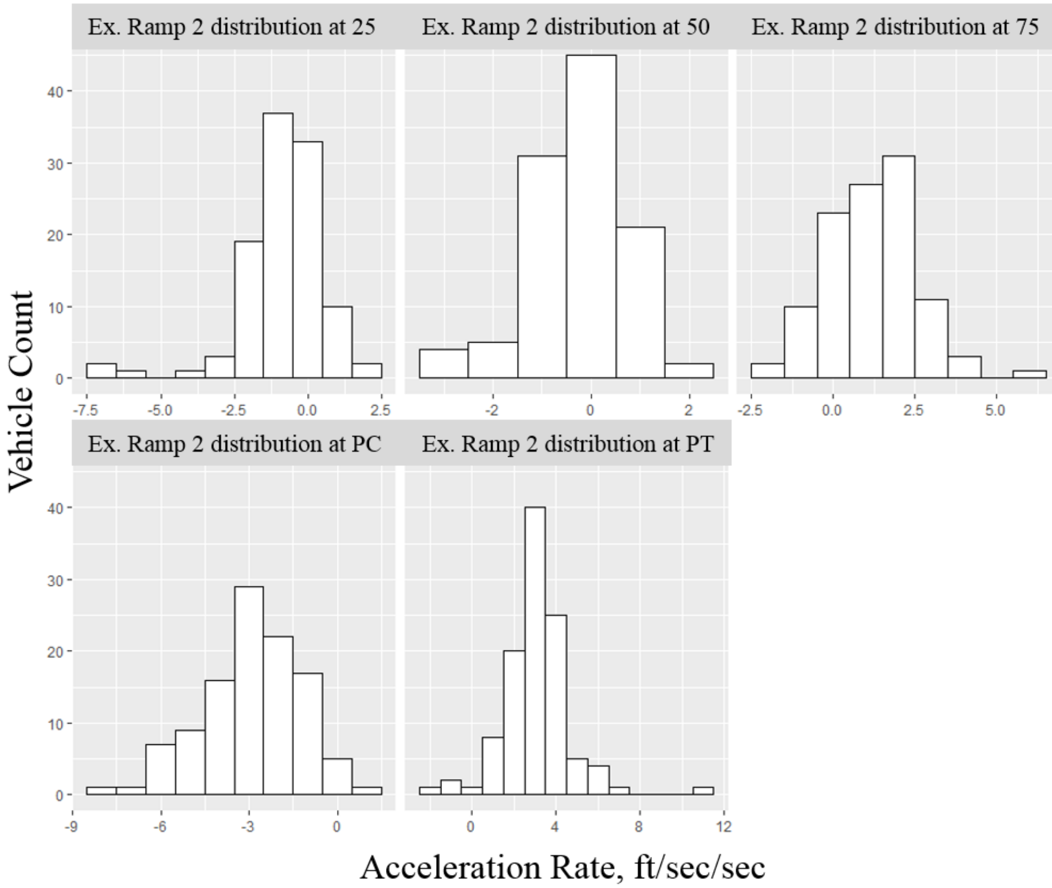

Figure B-2. Histograms of acceleration rate on Exit Ramp 2.

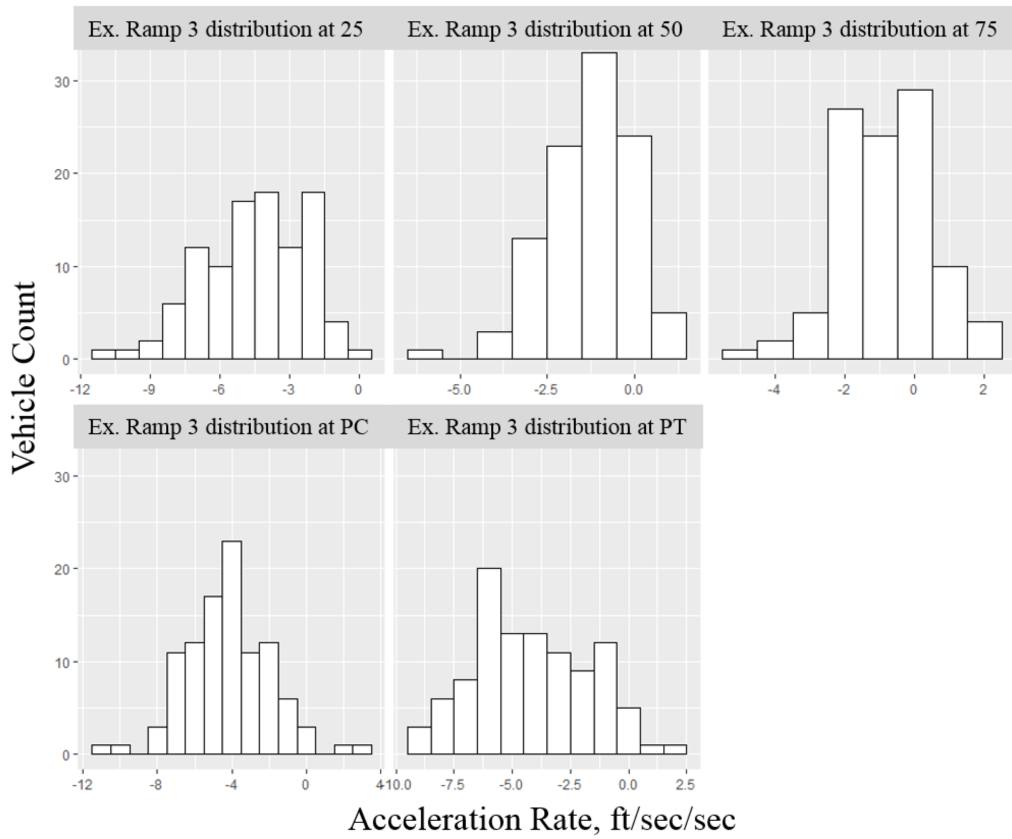

Figure B-3. Histograms of acceleration rate on Exit Ramp 3.

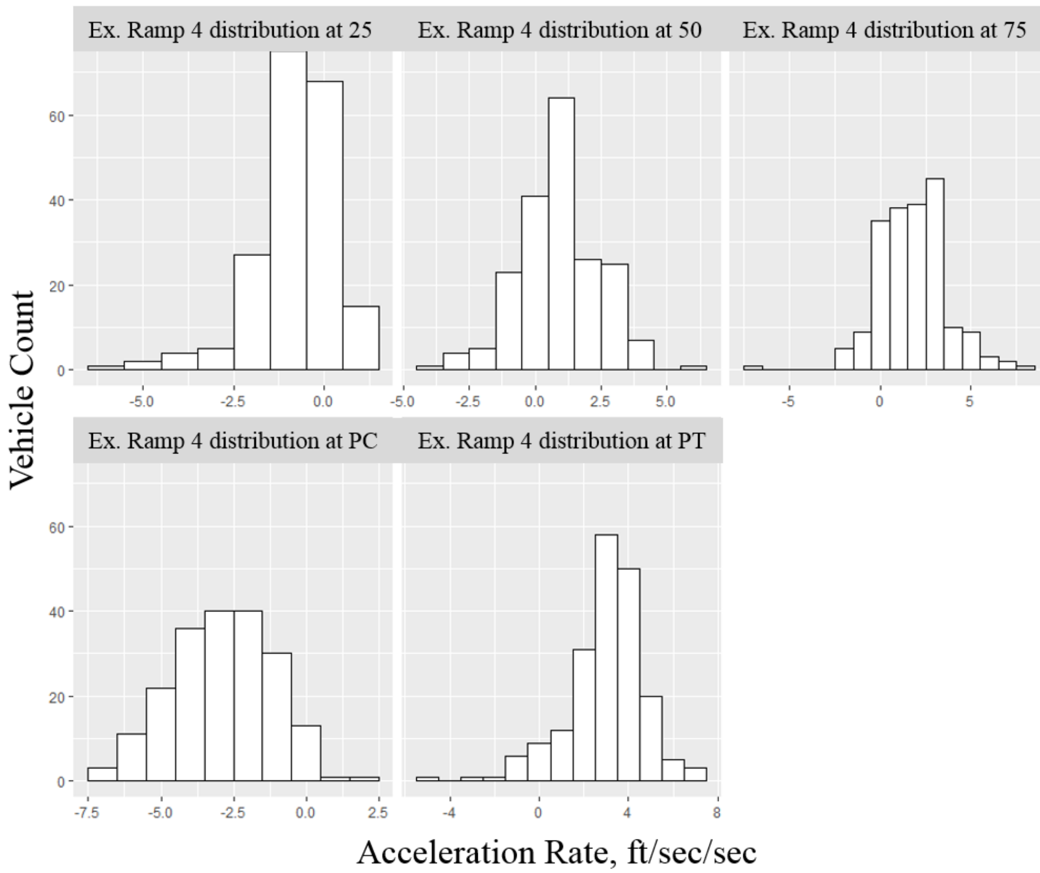

Figure B-4. Histograms of acceleration rate on Exit Ramp 4.

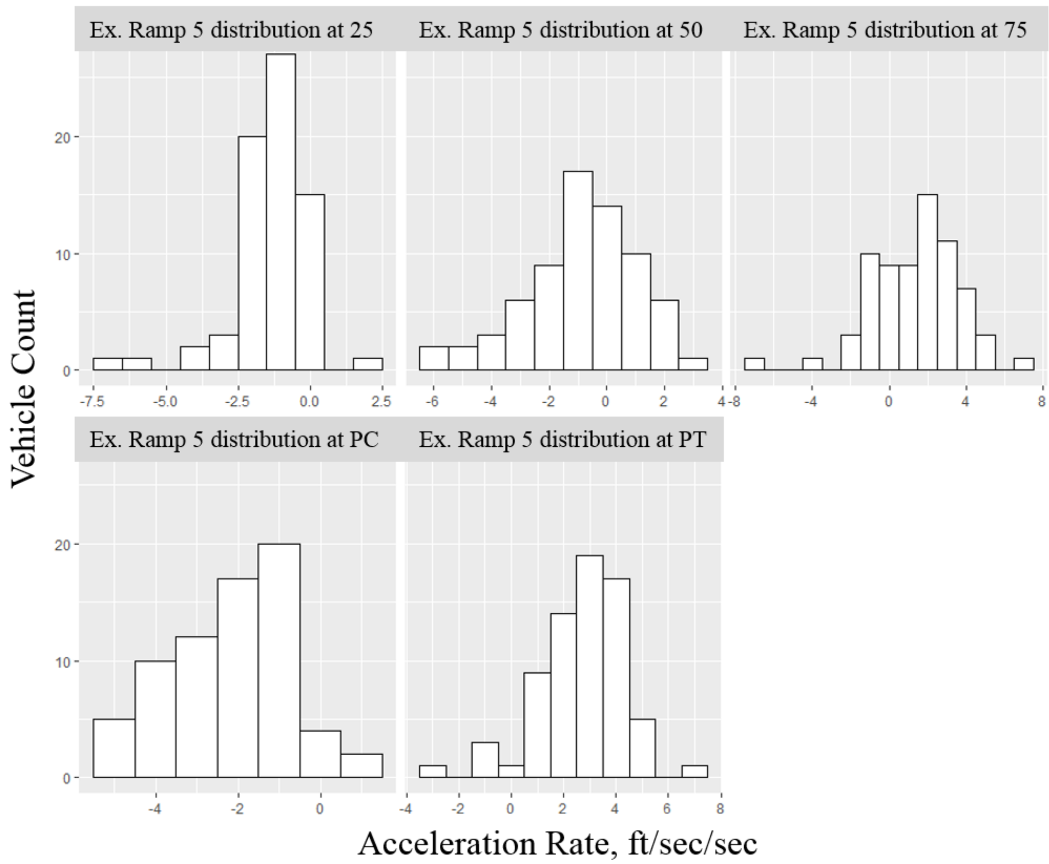

Figure B-5. Histograms of acceleration rate on Exit Ramp 5.

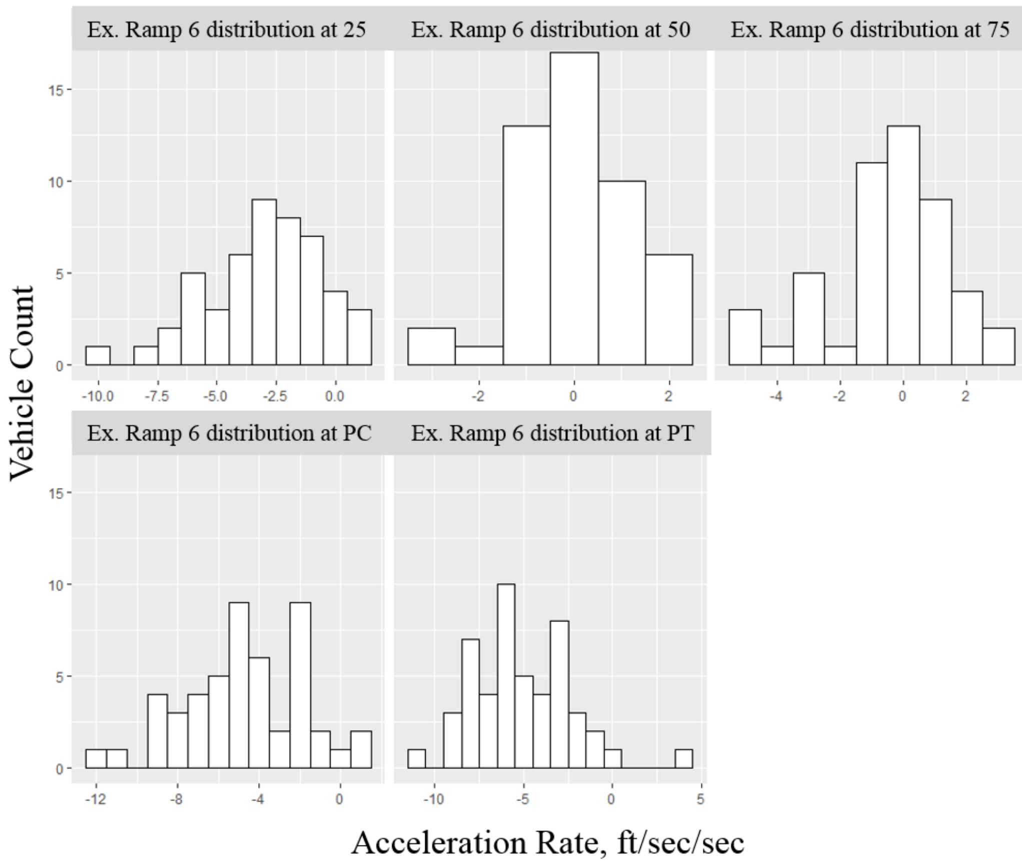

Figure B-6. Histograms of acceleration rate on Exit Ramp 6.

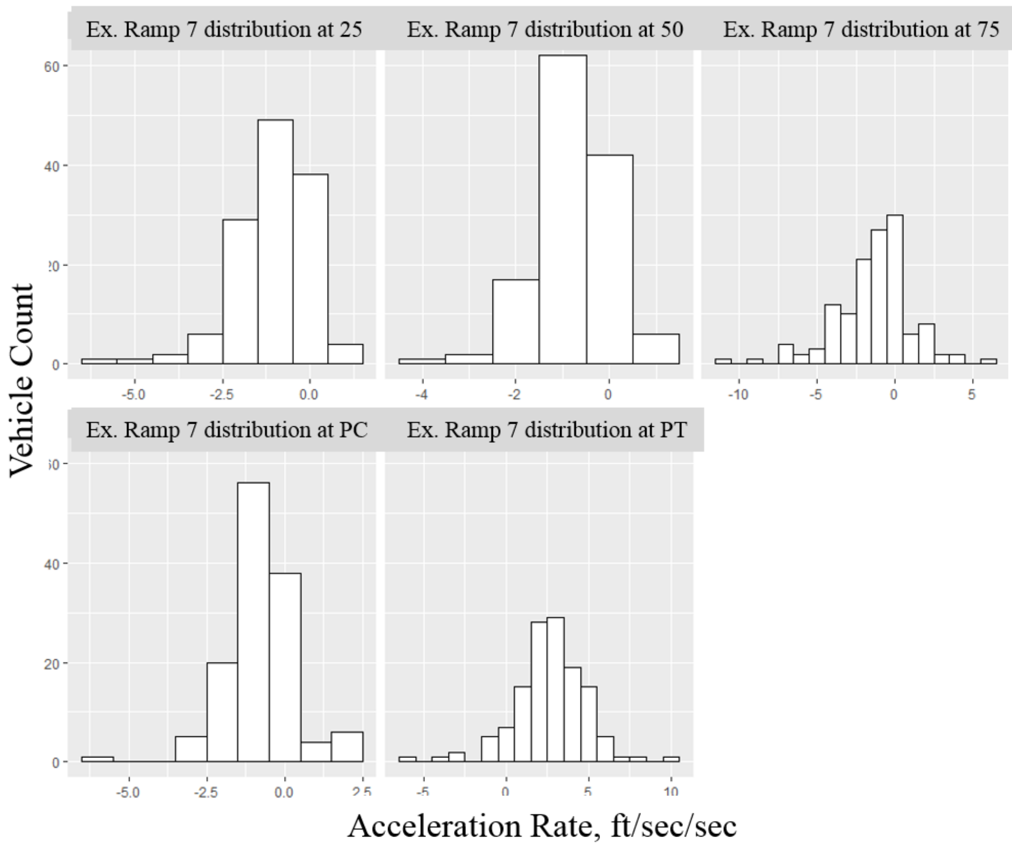

Figure B-7. Histograms of acceleration rate on Exit Ramp 7.

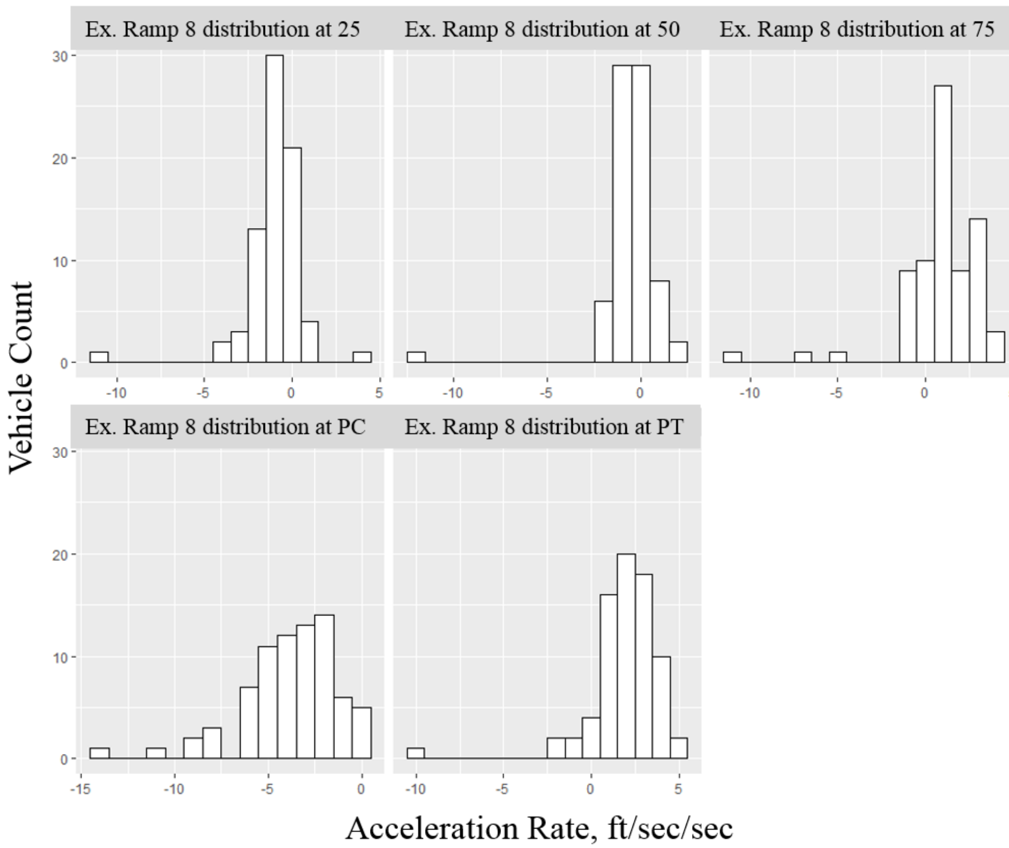

Figure B-8. Histograms of acceleration rate on Exit Ramp 8.

APPENDIX C

ACCELERATION HISTOGRAMS FOR EACH ENTRANCE RAMP

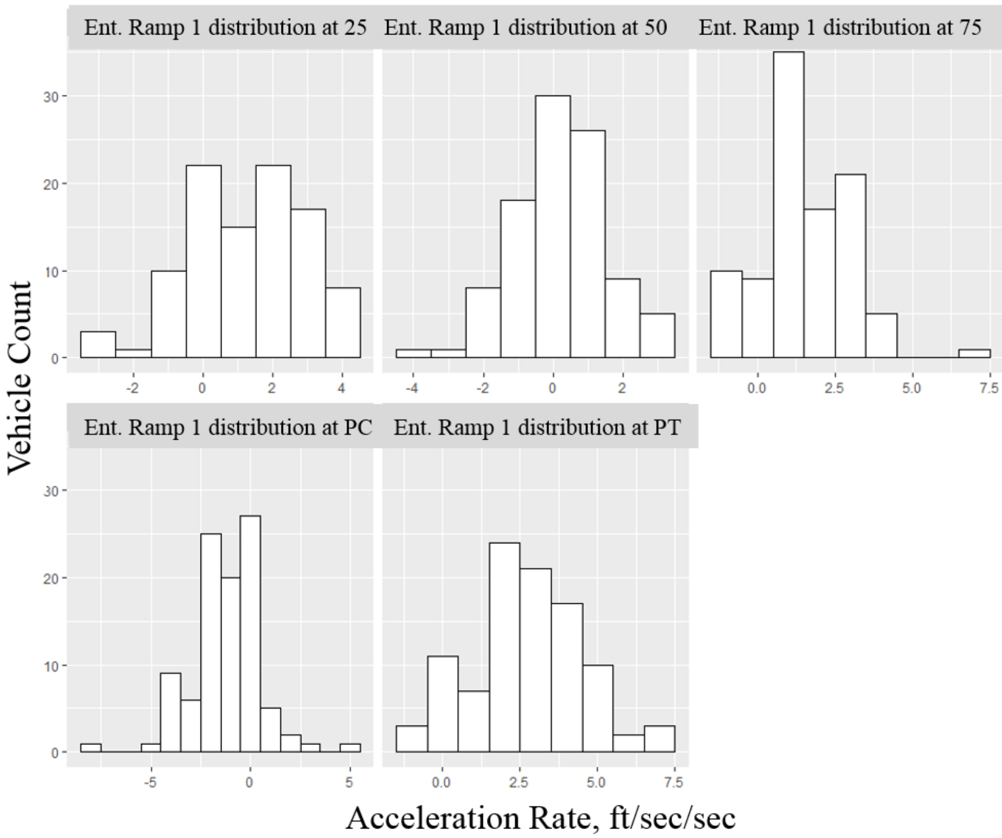

Figure C-1. Histograms of acceleration rate on Entrance Ramp 1.

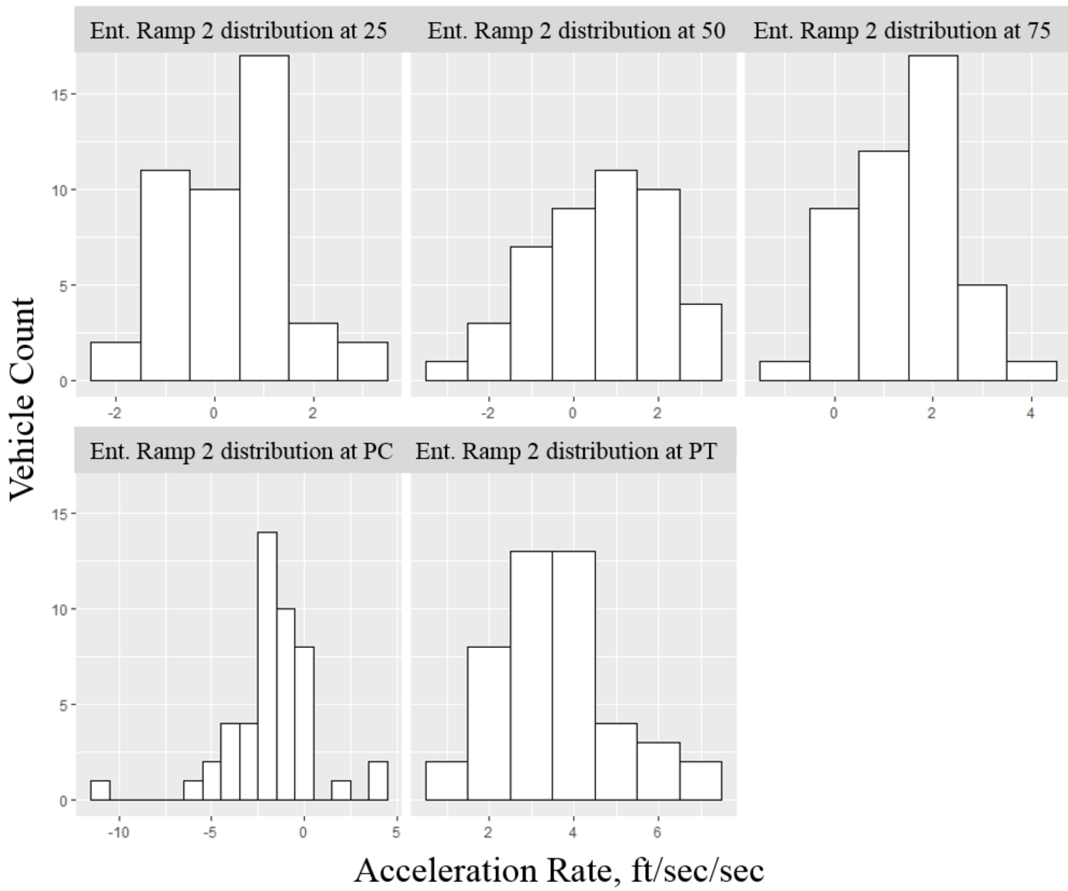

Figure C-2. Histograms of acceleration rate on Entrance Ramp 2.

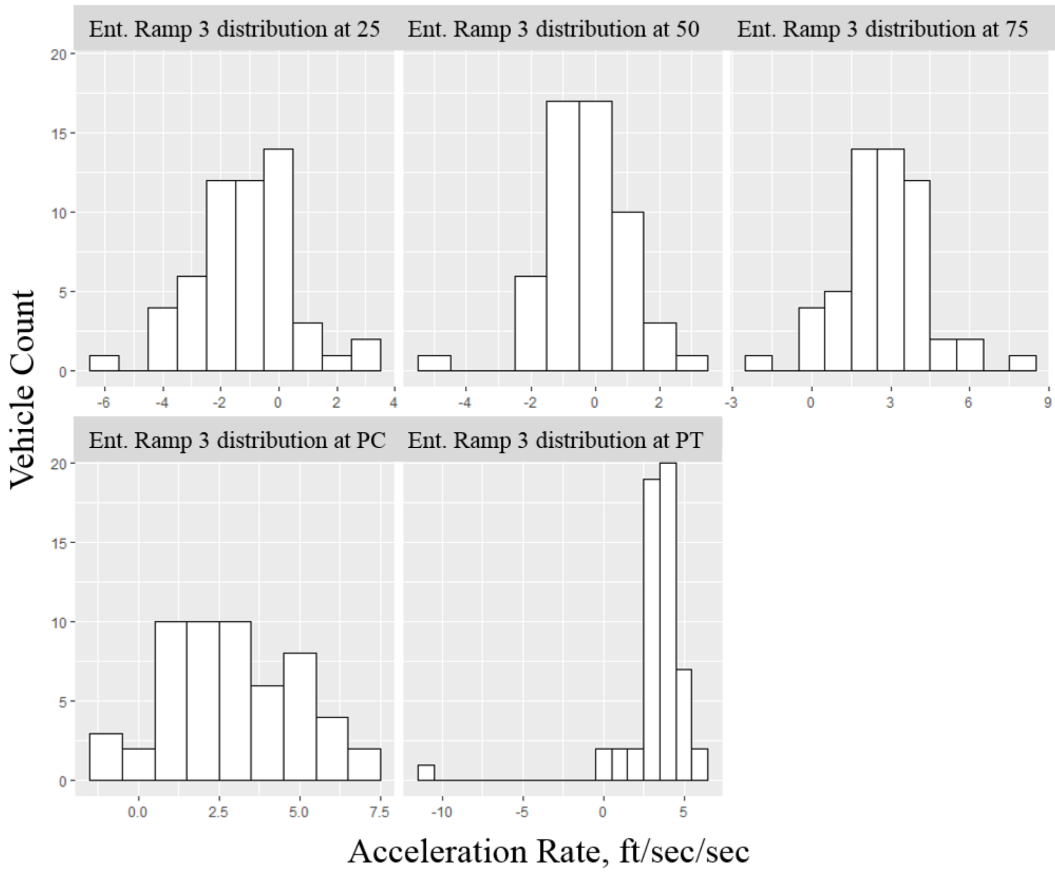

Figure C-3. Histograms of acceleration rate on Entrance Ramp 3.

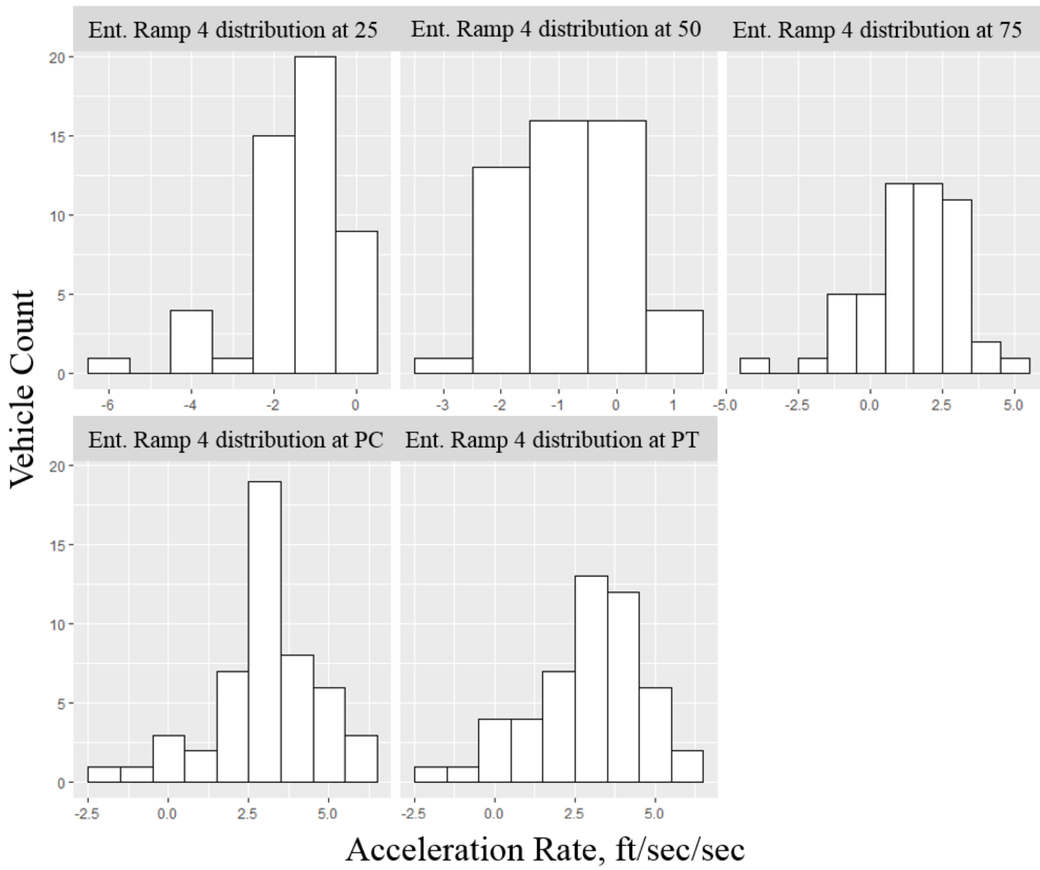

Figure C-4. Histograms of acceleration rate on Entrance Ramp 4.

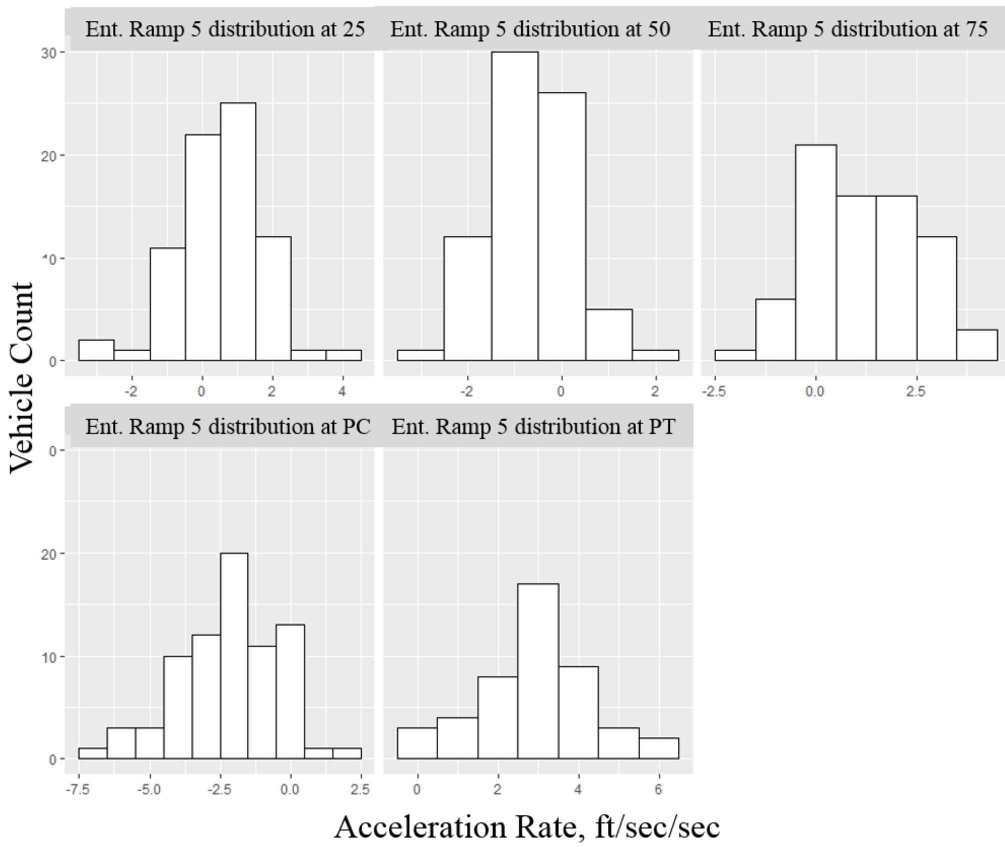

Figure C-5. Histograms of acceleration rate on Entrance Ramp 5.

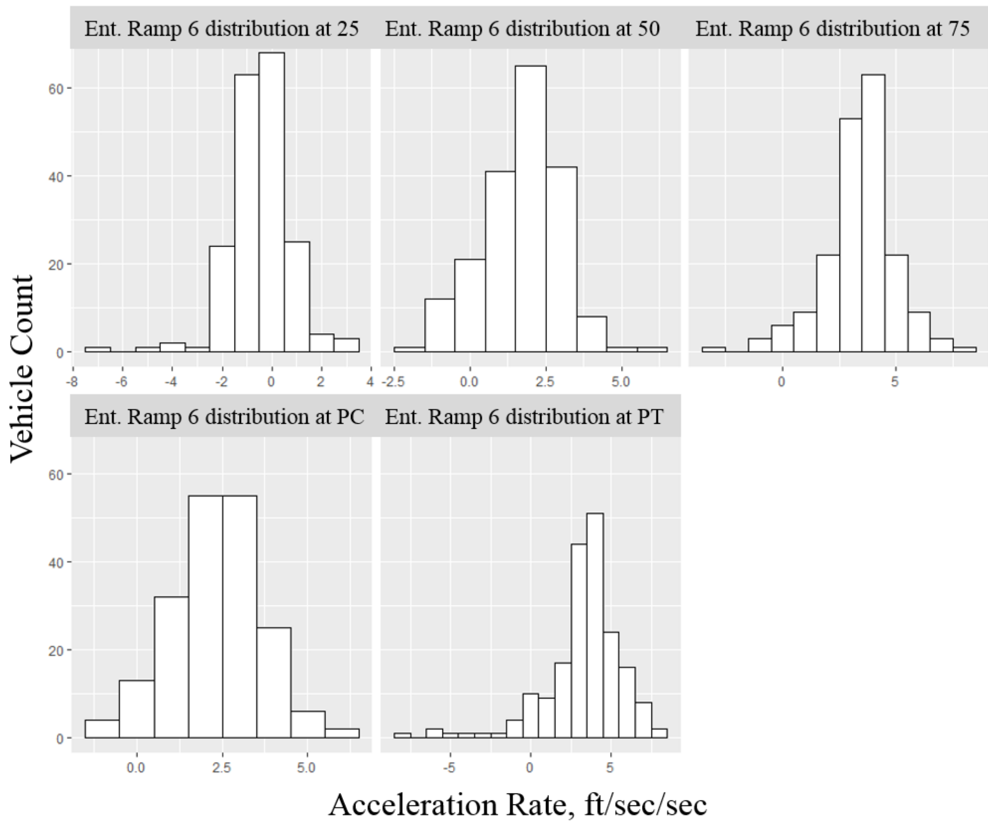

Figure C-6. Histograms of acceleration rate on Entrance Ramp 6.

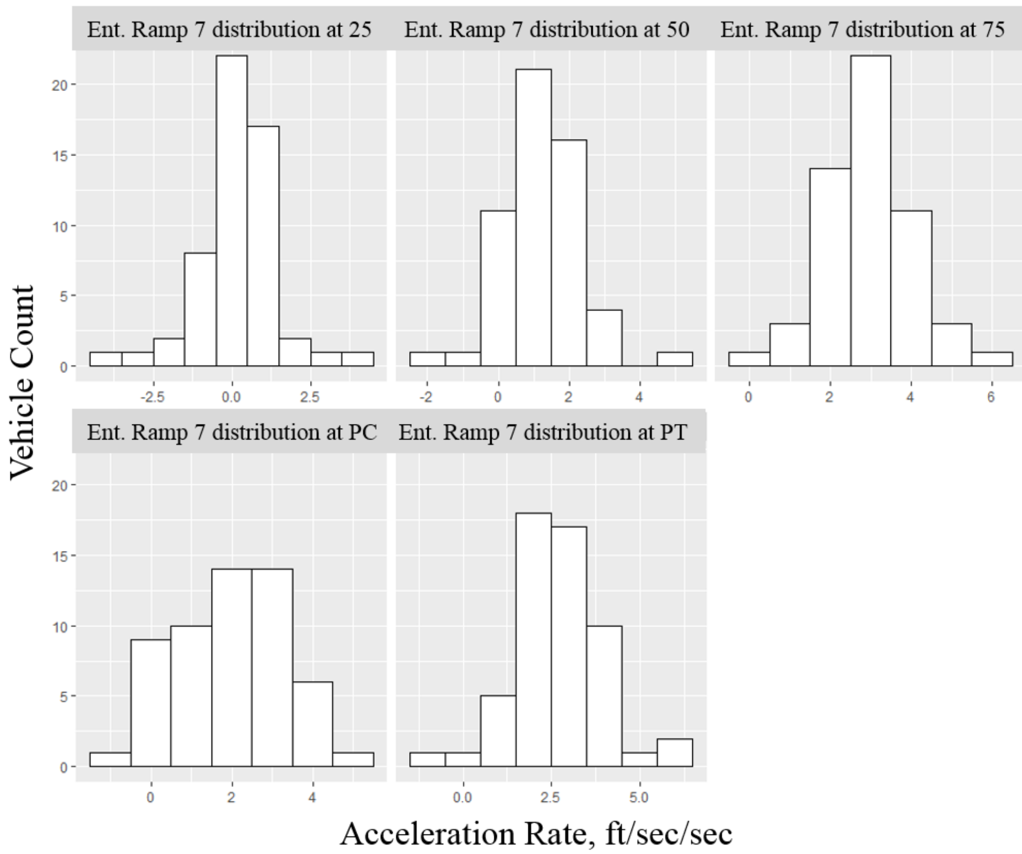

Figure C-7. Histograms of acceleration rate on Entrance Ramp 7.

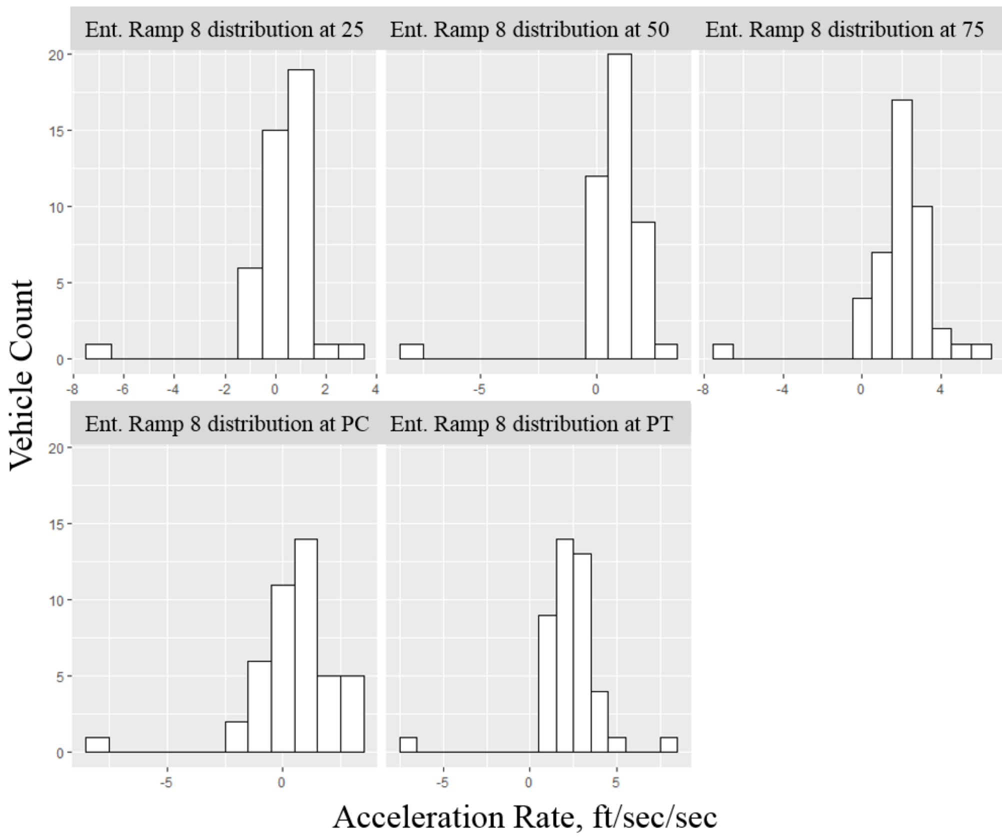

Figure C-8. Histograms of acceleration rate on Entrance Ramp 8.

APPENDIX D

STATISTICAL ANALYSIS FOR EXIT RAMPS

Figure D-1 shows the results for the effect of vehicle class on deceleration rate. As discussed in the main text, vehicle class was not found to significantly impact speed change rates on these loop ramps. To perform these calculations, the disaggregate data was used.

The SAS System

The GLM Procedure

Dependent Variable: X_0

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	6.960817	2.320272	0.35	0.7867
Error	778	5107.393371	6.564773		
Corrected Total	781	5114.354189			

R-Square	Coeff Var	Root MSE	X_0 Mean
0.001361	-81.82201	2.562181	-3.131408

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Vehicle_Class	3	6.96081749	2.32027250	0.35	0.7867

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Vehicle_Class	3	6.96081749	2.32027250	0.35	0.7867

Parameter	Estimate		Standard Error	t Value	Pr > |t|
Intercept	-3.179980834	B	0.48420675	-6.57	<.0001
Vehicle_Class CAR	0.081727271	B	0.49616427	0.16	0.8692
Vehicle_Class PICKUP_TRUCK	0.287794723	B	0.64560900	0.45	0.6559
Vehicle_Class SUV_CROSSOVER	-0.114836630	B	0.52536214	-0.22	0.8270
Vehicle_Class VAN_MINIVAN	0.000000000	B	.	.	.

Figure D-1. SAS Results for the effect of Vehicle Class at Exit Ramp PC.

Tables D-1 through D-3 show statistical analysis for the average freeway deceleration ratio on exit ramps. The statistical analysis shows that with the data used for this research, the model using only the ramp radius and the freeway speed limit performs better to models using those two variables and either ramp lane width or auxiliary lane width.

Table D-1. Statistical Analysis for $DR_{fwy,ave}$ Model on Exit Ramps with Only Two Variables

Regression Statistics	
Multiple R	0.993
R Square	0.987
Adjusted R Square	0.818
Standard Error	0.089
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	3.5811	1.7906	224.7351	1.27E-05
Residual	6	0.0478	0.0080		
Total	8	3.6289			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
RadQ1^2	-55.9949	15.5088	-3.6105	0.0112	-93.9435	-18.0463
FwySL	0.0147	0.0013	11.7641	0.0000	0.0117	0.0178

Table D-2. Statistical Analysis for $DR_{fwy,ave}$ Model on Exit Ramps with Lane Width

Regression Statistics	
Multiple R	0.995
R Square	0.990
Adjusted R Square	0.787
Standard Error	0.083
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	3.5943	1.1981	173.0967	0.00011
Residual	5	0.0346	0.0069		
Total	8	3.6289			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
RadQ1^2	-38.1205	19.4043	-1.9645	0.1067	-88.0008	11.7598
FwySL	0.0075	0.0053	1.4102	0.2176	-0.0062	0.0213
Total Lane Width	0.0276	0.0200	1.3808	0.2259	-0.0238	0.0791

Table D-3. Statistical Analysis for $\mathrm{DR}_{\mathrm{fwy,ave}}$ Model on Exit Ramps with Auxiliary Length

Regression Statistics	
Multiple R	0.948
R Square	0.898
Adjusted R Square	0.657
Standard Error	1.584
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	110.4258	36.8086	14.6738	0.0126
Residual	5	12.5423	2.5085		
Total	8	122.9681			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
RadQ1	-49.3162	36.2449	-1.3606	0.2317	-142.4867	43.8543
FwySL	-0.0190	0.0402	-0.4714	0.6572	-0.1224	0.0845
AuxLen	0.0020	0.0021	0.9370	0.3918	-0.0034	0.0073

Table D-4. Statistical Analysis for $DR_{fwy,ave}$ Model on Exit Ramps

Regression Statistics	
Multiple R	0.993
R Square	0.987
Adjusted R Square	0.818
Standard Error	0.089
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	3.5811	1.7906	224.7351	1.2696E-05
Residual	6	0.0478	0.0080		
Total	8	3.6289			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
RadQ1^2	-55.9949	15.5088	-3.6105	0.0112	-93.9435	-18.0463
Fwy SL	0.0147	0.0013	11.7641	0.0000	0.0117	0.0178

Table D-5. Statistical Analysis for $DR_{Q1,ave}$ Model on Exit Ramps

Regression Statistics	
Multiple R	0.959
R Square	0.919
Adjusted R Square	0.739
Standard Error	0.058
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.2302	0.1151	34.1596	0.0012
Residual	6	0.0202	0.0034		
Total	8	0.2504			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
RadQ2^2	-71.4840	23.5894	-3.0303	0.0231	-129.2051	-13.7629
Fwy SL	0.0044	0.0007	6.3217	0.0007	0.0027	0.0061

Table D-6. Statistical Analysis for $DR_{fwy,85}$ Model on Exit Ramps

Regression Statistics	
Multiple R	0.994
R Square	0.988
Adjusted R Square	0.819
Standard Error	0.100
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	4.9882	2.4941	248.8316	9.87E-06
Residual	6	0.0601	0.0100		
Total	8	5.0483			

	Coefficients	*Standard E*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
FwySL	0.0168	0.0014	11.9287	0.0000	0.0133	0.0202
RadQ1^2	-56.8683	17.3949	-3.2693	0.0171	-99.4320	-14.3045

Table D-7. Statistical Analysis for $DR_{Q1,85}$ Model on Exit Ramps

Regression Statistics	
Multiple R	0.960
R Square	0.921
Adjusted R Square	0.741
Standard Error	0.087
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.5331	0.2665	34.9463	0.0012
Residual	6	0.0458	0.0076		
Total	8	0.5789			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
FwySL	0.0062	0.0010	5.9526	0.0010	0.0037	0.0088
RadQ2^2	-86.8190	35.4890	-2.4464	0.0500	-173.6573	0.0194

Table D-8. Statistical Analysis for $\alpha_{PC,ave}$ Model on Exit Ramps

Regression Statistics	
Multiple R	0.951
R Square	0.904
Adjusted R Square	0.665
Standard Error	1.539
Observations	8

ANOVA

	df	SS	MS	F	Significance F
Regression	3	111.1253	37.0418	15.6390	0.0113
Residual	5	11.8428	2.3686		
Total	8	122.9681			

	Coefficients	Standard E	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
RadQ2	64.6322	0.0111	1.1068	0.3188	-0.0162	0.0407
FwySL	-0.0506	0.0533	-0.9501	0.3857	-0.1876	0.0863
RadQ1	-45.4168	0.0067	-1.2914	0.2530	-0.0257	0.0085

Table D-9. Statistical Analysis for $\alpha_{25,ave}$ Model on Exit Ramps

Regression Statistics	
Multiple R	0.950
R Square	0.903
Adjusted R Square	0.664
Standard Error	0.884
Observations	8

ANOVA

	df	SS	MS	F	Significance F
Regression	3	36.2034	12.0678	15.4545	0.0115
Residual	5	3.9043	0.7809		
Total	8	40.1078			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
RadQ1	-51.8933	0.0038	-2.5699	0.0500	-0.0197	0.0000
RadQ2	55.5546	0.0064	1.6569	0.1584	-0.0058	0.0268
FwySpd	-0.0107	0.0306	-0.3488	0.7414	-0.0893	0.0680

Table D-10. Statistical Analysis for $\alpha_{PC,85}$ Model on Exit Ramps

Regression Statistics	
Multiple R	0.961
R Square	0.923
Adjusted R Square	0.692
Standard Error	2.224
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	296.8233	98.9411	19.9981	0.0072
Residual	5	24.7377	4.9475		
Total	8	321.5610			

	Coefficients	*Standard Erro*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
RadQ1	-72.8221	50.8279	-1.4327	0.2114	-203.4793	57.8351
FwySL	-0.0789	0.0770	-1.0252	0.3523	-0.2769	0.1190
RadQ2	96.6714	84.3961	1.1454	0.3039	-120.2757	313.6185

Table D-11. Statistical Analysis for $\alpha_{25,85}$ Model on Exit Ramps

Regression Statistics	
Multiple R	0.956
R Square	0.914
Adjusted R Square	0.679
Standard Error	1.422
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	107.2756	35.7585	17.6807	0.0090
Residual	5	10.1123	2.0225		
Total	8	117.3879			

	Coefficients	*Standard*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
RadQ1	-81.3590	32.4973	-2.5036	0.0543	-164.8961	2.1781
FwySL	-0.0204	0.0492	-0.4137	0.6962	-0.1469	0.1062
RadQ2	83.3050	53.9596	1.5438	0.1833	-55.4025	222.0125

APPENDIX E

STATISICAL ANALYSIS FOR ENTRANCE RAMPS

Figure E-1 shows the results for the effect of vehicle class on acceleration rate. As discussed in the main text, vehicle class was not found to significantly impact speed change rates on these loop ramps. To perform these calculations, the disaggregate data was used.

The SAS System

The GLM Procedure

Dependent Variable: X_100

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	12.538221	4.179407	1.11	0.3458
Error	640	2417.560179	3.777438		
Corrected Total	643	2430.098399			

R-Square	Coeff Var	Root MSE	X_100 Mean
0.005160	64.24227	1.943563	3.025365

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Vehicle_Class	3	12.53822072	4.17940691	1.11	0.3458

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Vehicle_Class	3	12.53822072	4.17940691	1.11	0.3458

Parameter	Estimate		Standard Error	t Value	Pr > |t|
Intercept	3.000161818	B	0.33833092	8.87	<.0001
Vehicle_Class CAR	-0.053672267	B	0.35018056	-0.15	0.8782
Vehicle_Class PICKUP_TRUCK	0.344076515	B	0.46839795	0.73	0.4629
Vehicle_Class SUV_CROSSOVER	0.256200497	B	0.38496095	0.67	0.5060
Vehicle_Class VAN_MINIVAN	0.000000000	B	.	.	.

Figure E-1. SAS Results for the effect of Vehicle Class at Entrance Ramp PT.

As with the exit ramp models, the statistical analysis showed that the models were strongest with only the two variables of ramp radius and freeway speed limit, as shown in Tables E-1 through E-3.

Table E-1. Statistical Analysis for $SD_{fwy,ave}$ Model on Entrance Ramps with Only Two Variables

Regression Statistics	
Multiple R	0.996125374
R Square	0.992265761
Adjusted R Square	0.824310055
Standard Error	2.806022438
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	6060.995419	3030.498	384.8856	3.34573E-06
Residual	6	47.24257152	7.873762		
Total	8	6108.237991			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
RadQ4	-85.67865137	36.06809368	-2.37547	0.055108	-173.9340972	2.576794501
FwySL	0.533137828	0.04343479	12.27444	1.78E-05	0.426856726	0.639418931

Table E-2. Statistical Analysis for $SD_{fwy,ave}$ Model on Entrance Ramps with Lane Width

Regression Statistics	
Multiple R	0.996444868
R Square	0.992902376
Adjusted R Square	0.790063326
Standard Error	2.944621472
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	6064.884013	2021.628	233.1537	6.05085E-05
Residual	5	43.35397806	8.670796		
Total	8	6108.237991			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
RadQ4	-96.2345093	41.0006344	-2.34715	0.065793	-201.6299953	9.160976737
FwySL	0.425181616	0.167525772	2.538007	0.05202	-0.00545709	0.855820323
Total Lane Width	0.487069936	0.727318321	0.669679	0.53274	-1.382561329	2.356701201

Table E-3. Statistical Analysis for $SD_{fwy,ave}$ Model on Entrance Ramps with Auxiliary Length

Regression Statistics	
Multiple R	0.996400896
R Square	0.992814745
Adjusted R Square	0.789940643
Standard Error	2.962743543
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	6064.348745	2021.45	230.2898	6.20126E-05
Residual	5	43.8892465	8.777849		
Total	8	6108.237991			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
RadQ4	-66.42198663	49.20323076	-1.34995	0.234923	-192.9029179	60.05894462
FwySL	0.529598104	0.046216899	11.45897	8.87E-05	0.410793782	0.648402426
AuxLen	-0.002765169	0.004473814	-0.61808	0.563587	-0.014265473	0.008735136

Table E-4. Statistical Analysis for $SD_{fwy,ave}$ Model on Entrance Ramps

Regression Statistics	
Multiple R	0.995
R Square	0.990
Adjusted R Square	0.822
Standard Error	2.644
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	4174.2167	2087.1083	298.5294	6.29E-06
Residual	6	41.9478	6.9913		
Total	8	4216.1645			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
RadQ4	-88.2209	0.0064	-2.5957	0.0409	-0.0325	-0.0010
FwySL	0.4609	0.0409	11.2615	0.0000	0.3608	0.5611

Table E-5. Statistical Analysis for $SD_{Q4,ave}$ Model on Entrance Ramps

Regression Statistics	
Multiple R	0.987
R Square	0.973
Adjusted R Square	0.802
Standard Error	1.020
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	228.6057	114.3028	109.9193	7.37E-05
Residual	6	6.2393	1.0399		
Total	8	234.8449			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
RadQ4	14.9561	0.0025	1.1410	0.2973	-0.0032	0.0089
FwySL	0.0682	0.0158	4.3182	0.0050	0.0295	0.1068

Table E-6. Statistical Analysis for $SD_{fwy,85}$ on Entrance Ramps

Regression Statistics	
Multiple R	0.996
R Square	0.992
Adjusted R Square	0.824
Standard Error	2.806
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	6060.9954	3030.4977	384.8856	3.35E-06
Residual	6	47.2426	7.8738		
Total	8	6108.2380			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
RadQ4	-85.6787	0.0068	-2.3755	0.0551	-0.0329	0.0005
FwySL	0.5331	0.0434	12.2744	0.0000	0.4269	0.6394

Table E-7. Statistical Analysis for $SD_{Q4,85}$ Model on Entrance Ramps

Regression Statistics	
Multiple R	0.995
R Square	0.990
Adjusted R Square	0.822
Standard Error	0.919
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	507.0674	253.5337	300.5219	6.18E-06
Residual	6	5.0619	0.8436		
Total	8	512.1292			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
RadQ4	23.0203	0.0022	1.9498	0.0991	-0.0011	0.0098
FwySL	0.1007	0.0142	7.0795	0.0004	0.0659	0.1354

Table E-8. Statistical Analysis for $\alpha_{PT,ave}$ Model on Entrance Ramps

Regression Statistics	
Multiple R	0.983
R Square	0.966
Adjusted R Square	0.823
Standard Error	0.587
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	68.9899	68.9899	200.2893	7.77E-06
Residual	7	2.4112	0.3445		
Total	8	71.4011			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
FwySpeed	0.0468	0.0033	14.1524	0.0000	0.0390	0.0546

Table E-9. Statistical Analysis for $\alpha_{75,ave}$ Model on Entrance Ramps

Regression Statistics	
Multiple R	0.947
R Square	0.896
Adjusted R Square	0.753
Standard Error	0.763
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	35.2204	35.2204	60.5356	0.0002
Residual	7	4.0727	0.5818		
Total	8	39.2930			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
FwySpeed	0.0334	0.0043	7.7805	0.0001	0.0233	0.0436

Table E-10. Statistical Analysis for $\alpha_{PT,85}$ Model on Entrance Ramps

Regression Statistics	
Multiple R	0.979
R Square	0.958
Adjusted R Square	0.815
Standard Error	1.007
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	160.0289	160.0289	157.8419	1.56E-05
Residual	7	7.0970	1.0139		
Total	8	167.1259			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
FwySpeed	0.0713	0.0057	12.5635	0.0000	0.0579	0.0847

Table E-11. Statistical Analysis for $\alpha_{75,85}$ Model on Entrance Ramps

Regression Statistics	
Multiple R	0.979
R Square	0.958
Adjusted R Square	0.816
Standard Error	0.776
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	97.1150	97.1150	161.4302	1.46E-05
Residual	7	4.2111	0.6016		
Total	8	101.3262			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
FwySpeed	0.0555	0.0044	12.7055	0.0000	0.0452	0.0659