

# Development of Analytic Method to Determine Weaving Patterns for Safety Analysis near Freeway Interchanges with Access Management Treatments

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Final Report



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16. Abstract Urban arterials near freeway interchanges are vital elements of urban road infrastructures. They connect freeway network with high mobility and low access to urban network with lower mobility and higher access. This study investigates the operational safety of these elements and tries to find the relationship between geometric elements of roadway and the operational safety of urban arterials near interchanges. To measure the operational safety of urban arterials, the authors assumed lane changing as a risk factor and counted the number of lane changes over each study segment. Study segments were grouped to represent if they were located upstream to the freeway entrance or downstream to the freeway exit. The number of lane changes was used to define a new safety performance measure and was used as the dependent variable. Linear regression was used to construct statistical models. The results of this study showed that for downstream segments providing a median storage was the factor with the highest coefficient which means that median storages inversely impacted the safety performance of the roads. Adding a right running bay improved the safety performance of downstream segments, while having median openings and adding more driveways negatively impacted the safety performance of the study segments. For upstream segments right turning bays impaired the safety of the performance. Moreover, the number of driveways and proximity of the driveways were the next two factors with the highest negative impact on the safety performance of the roads.			
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## Abstract

*Urban arterials near freeway interchanges are vital road infrastructure segments since they connect two significantly different types of roads—freeways and urban arterials. While freeways are high mobility and low access, urban arterials are medium mobility and high access. This study used data from numerous resources for a different approach to evaluating safety. Researchers defined a new safety performance measure to evaluate the fluctuation between the number of lane changes in small subsets of each study segment near diamond interchanges. The study focused on the impact that design options have on lane change fluctuations on an urban arterial. The results show that the existence of auxiliary right turn lanes, number of driveways, and number and characteristics of median, impact fluctuations the most. A linear regression model was proposed to formulate this relationship individually for both upstream and downstream segments.*

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## TABLE OF CONTENTS

<b>INTRODUCTION .....</b>	<b>1</b>
<b>BACKGROUND.....</b>	<b>1</b>
Impact of Lane Changes on Traffic Flow .....	1
Performance Measure Selection.....	3
Variable Selection.....	4
Distance Between First Signalized Intersection and Terminal Intersection .....	4
Left Turning Vehicles.....	5
Right Turning Vehicles .....	6
Driveway Entrance Speed .....	7
Access Density.....	7
Median Treatment.....	8
Corner Clearance (First Driveway) .....	9
Simulation.....	9
Model Validation.....	10
Independent Samples T-test.....	11
Confidence Interval Approach.....	12
Linear Regression.....	13
Variable Selection.....	13
<b>METHOD .....</b>	<b>14</b>
<b>RESULTS.....</b>	<b>19</b>
Descriptive Statistics.....	19
Paired t-tests .....	20
<b>DISCUSSION .....</b>	<b>23</b>
<b>CONCLUSIONS AND RECOMMENDATIONS .....</b>	<b>25</b>
<b>ADDITIONAL PRODUCTS .....</b>	<b>26</b>
Education and Workforce Development Products .....	26

Technology Transfer Products .....26

Data Products .....26

REFERENCES.....27

## List of Figures

Figure 1. Leisch graphs for one sided weaving section lengths – source: [30].....	5
Figure 2. Relationship between delay and driveway entrance speed. – source: [35] .....	7
Figure 3 Simulation model sketch. ....	15
Figure 4. Collected design and operation variables for study segments. ....	16
Figure 5. Density plot of CV for all segments. ....	19
Figure 6. Histograms of coefficient of variation for even and odd segments. ....	19
Figure 7. Scenario Options Boxplots. ....	20
Figure 8. R2 scores for different lambda values. ....	22

## List of Tables

Table 1. Classification of Lane Change Maneuvers Present at an Urban Arterial near an Interchange – Source: [31] .....	6
Table 2. Reduction in Free Flow Speed on Highways Based on Number of Access Points. – Source: [27] .....	7
Table 3. Minimum distances between median openings. – source: [35].....	8
Table 4. z and t values for commonly used confidence levels. ....	12
Table 5. Scenario Settings Based on Different Options.....	15
Table 6. Paired t-test results. ....	20
Table 7. Coefficients table for the comprehensive model.....	22
Table 8. Coefficients table for upstream segments.....	22
Table 9. Coefficients table for downstream segments. ....	23
Table 10. Largest coefficients for the comprehensive model.....	24
Table 11. Largest coefficients for downstream segments. ....	24
Table 12. Largest coefficients for upstream segments.....	24

# Introduction

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Interchanges where freeway networks meet urban networks are important, as they facilitate the transition between two different driving environments, are host to a high number of commercial land uses, and service different demand and land use types. Transportation designers and planners face several questions when designing interchanges. How far should the interchange be placed from the signalized intersections? How far from the interchange should the first access point be or how many access points should a shopping plaza have? Should right turns at the terminal intersection be stop- or yield-controlled? [1]. This study used numerous data sources and implemented simulation techniques to build a database with different options and analyzed the data to evaluate the relationship between design options and safety performance of selected study locations. Two models were proposed to analyze these relationships and suggest the best design options.

## Background

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Urban roads in the U.S. account for roughly 25% of all roads, while they carry about two thirds of vehicle miles traveled (VMT) [2–4]. According to TRB Special Report 260, Strategic Highway Research, VMT is expected to further increase in the upcoming years [5], emphasizing the importance of optimal transportation network management, as there is often little room to expand the physical infrastructure.

Researchers have studied almost every roadway design element. Many of the earlier studies focused on economic evaluations of roadway features. The early study trend was to measure costs based on injuries, deaths, or other losses. Example studies from this line of research considered the number of lanes [6] [7], lane width [7], surface type [8], cross slope [9], and surface friction [10]. Cribbins et al. [11] evaluated median width, while Foley [12] investigated the frequency of median openings and the type of median barriers. Auxiliary lanes, such as left turn lanes and transition lanes (for speed adjustment), as well as shoulder and roadside characteristics, vertical alignment, traffic control devices have also received much attention. Avelar et al. [13] categorized parameters that influenced arterial highway safety into the following seven categories, namely driveway spacing, proximity to interchange and intersection, traffic signal control, driveway type, roadway characteristics, land use, and median type. Their research concluded that segment length, Average Annual Daily Traffic (AADT), median type (Two Way Left Turn Lane- TWLTL) and having four lanes on the rural highway were the most significant factors contributing to highest number of crashes.

## Impact of Lane Changes on Traffic Flow

Lane changes impact traffic flow in different ways. In some cases, vehicles adjust their speeds to seek an acceptable gap in the target lane, causing a disturbance in the traffic flow. In other cases,



where there is an adequate gap, lane changes take place as a response to the vehicle's location on the road and the available distance to maneuver. In both cases, design and operational characteristics impact the location and frequency of lane changes.

As part of a lane change maneuver, vehicles first take up space in their present lane and then seek adequate space in the adjacent lane. This means that lane-changing vehicles use more space than non-lane-changing vehicles. Jin incorporated kinematic wave theory to study the impact of lane changing on traffic flow. He introduced a lane changing intensity factor and postulated that when a vehicle changes lanes, it needs to have two spaces dedicated to the process [14]. The fundamental traffic flow equation has the form:

$$q = \rho v \quad (1)$$

Where:

- $q$  is the flow rate,
- $\rho$  is the density and
- $v$  is the speed.

In the presence of lane change maneuvers an intensity factor,  $\varepsilon$  is introduced and the fundamental equation can be written as:

$$q = (1 + \varepsilon)\rho V((1 + \varepsilon)\rho) \quad (2)$$

where speed is dependent on density ( $v = V(\rho)$ ). Equation (2) shows that lane changing impacts traffic flow by increasing density.

In a study of single point urban interchanges, Messer and Bonneson noted that the traffic flow on arterial crossroads experiences turbulence due to these roads' high volume of lane changes [15]. However, while the authors reported this turbulence, they did not quantify it. Numerous other studies have reported that lane changing can cause drops in capacity [16] and can have a direct influence on traffic safety [17]. The lane changing models that can be incorporated in simulation software are microscopic models that take a close look at the interactions between individual vehicles as lane changes happen.

From the first lane changing model introduced by Gipps [18] to the more recent, such as the MOBIL model [17], all models have studied lane changing in the context of the traveled path. These models regard lane changing as an interaction among two or more vehicles and ignore the impact of design elements on the recurrence and location of lane changes. As another example, Laval and Daganzo [19] proposed a hybrid approach, combining acceleration and a kinematic wave model, to address the impact of lane changing on freeways where the studied lane changing maneuvers had the sole purpose of increasing speed (discretionary lane changes). They calculated number of lane changing maneuvers for each lane of the freeway but did not incorporate design and operational characteristics of the traveled path in their calculations. While lane changing

models are useful, they do not account for roadway characteristics and cannot be used to design roadways that are resilient to the inverse impact of lane changing.

Surrogate safety measures are measures such as Deceleration Rate to Avoid the Crash (DRAC), Post Encroachment Time (PET), Time to Collision (TTC) and similar measures have been used in several studies and applications, such as the Surrogate Safety Assessment Model application developed by the Federal Highway Safety Administration. A comprehensive review of these measures are presented in Gettman and Head [21].

More recently, Iliadi et al. [22] developed a crash prediction model for “type A” weaving sections—as defined by Highway Capacity Manual (HCM) classification—on freeways. The authors developed a negative binomial regression model and used average annual daily traffic, length of weaving section, number of lanes, and proportion of weaving vehicles. Glad et al. [23], Golob et al. [24], Liu et al. [25], and Park et al. [26] have all studied the safety aspects of freeway weaving areas. However, none of these referenced studies has focused on arterials in the vicinity of interchanges.

## Performance Measure Selection

Candidate performance measures should support the goals of the associated study. The National Cooperative Highway Research Program (NCHRP) Synthesis 311 titled *Performance measures of operational effectiveness for highway segments and systems* lists the performance measures commonly used by researchers for analysis [6]. Based on this study, level of service (LOS) and traffic volume each account for 11% of the performance measure choices made by researchers and engineers. VMT, travel time, and volume are also listed as other common performance measures, accounting for 10%, 8%, and 11% of choices respectively.

The HCM uses different performance measures to evaluate LOS on different transportation facilities [27]. LOS on urban streets (HCM, Chapter 15) is evaluated by calculating speed. LOS is determined based on delay at signalized intersections (HCM, Chapter 16), and two-way stop-controlled intersections and T-intersections (Chapter 17).

The research team used a new performance measure in this study. Since the number of lane changes fluctuated on the study segments, the authors divided each study segment into five subsegments of equal lengths and extracted the number of lane changes. Next, the coefficients of variation (CV) of the number of lane changes were calculated and used as the safety performance measure of each study segment. The CV is a standardized measure that describes the level of variability in a population independently of the absolute values of the observations. This makes the CV a fitting representation of the fluctuation in the number of lane changes in subsegments along a segment without imparting unknown or unmeasured variables that may affect the number of lane changes at different study sites. Examples of unknown or unmeasured variables include driver behavior, laws and regulations, land use, and weather conditions, which can vary among different study sites. The CV is calculated by dividing the standard deviation by the mean:

$$CV = \frac{SD}{\bar{x}} \quad (3)$$

Since the CV is usually represented as a percent, this variable is designed as flux:

$$flux = 100 * CV \quad (4)$$

Flux is dimensionless and is used as the dependent variable in statistical modeling.

## Variable Selection

As previously noted, during past decades, researchers have studied almost every roadway design element. Many of these studies focused on economic evaluations of roadway features. The following sections review and summarize studies that have focused on geometric- and access-related design parameters.

### Distance Between First Signalized Intersection and Terminal Intersection

The first published literature on the impact of weaving section lengths dates back to 1970. Conducted by Cirillo [28], this study investigated the relationship between the number of merge and diverge movements and the number of crashes on urban freeways. The author found that for average daily traffic values over 10,000 vehicles per day, the length of the weaving area increased along with the number of crashes at the study sites. Cirillo also found that the percentage of merging and diverging vehicles contributed to the crash rate and that the crash rate increased as the proportion of merging and diverging vehicles increased.

Signalized intersections located too close to the interchange can negatively impact signal operation or cause excessive weaving maneuvers. NCHRP Report 420 suggested that travel time increased by up to 39% when there were 8 signals per mile [23].

An Oregon Department of Transportation (DOT) research project suggested placing the first intersection no closer than 1,320 feet and the first access point (driveway or median) at least 750 feet away from the ramp entrance for two-lane crossroads. For four-lane crossroads, 2,640 feet was the suggested minimum distance for the first major signalized intersection, with the first access point to be placed at 750 feet, and a suggested distance for the first median 990 feet [29]. These guidelines were based on sight distance, weaving, merging, and left-turn storage requirements. The weaving distance in the Oregon DOT study was calculated based on Leisch graphs that calculate that distance based on speed and weaving volume [30]. Figure 1 illustrates an example of Leisch graphs for one-sided weaving sections. Leisch developed similar graphs for two-sided weaving sections.

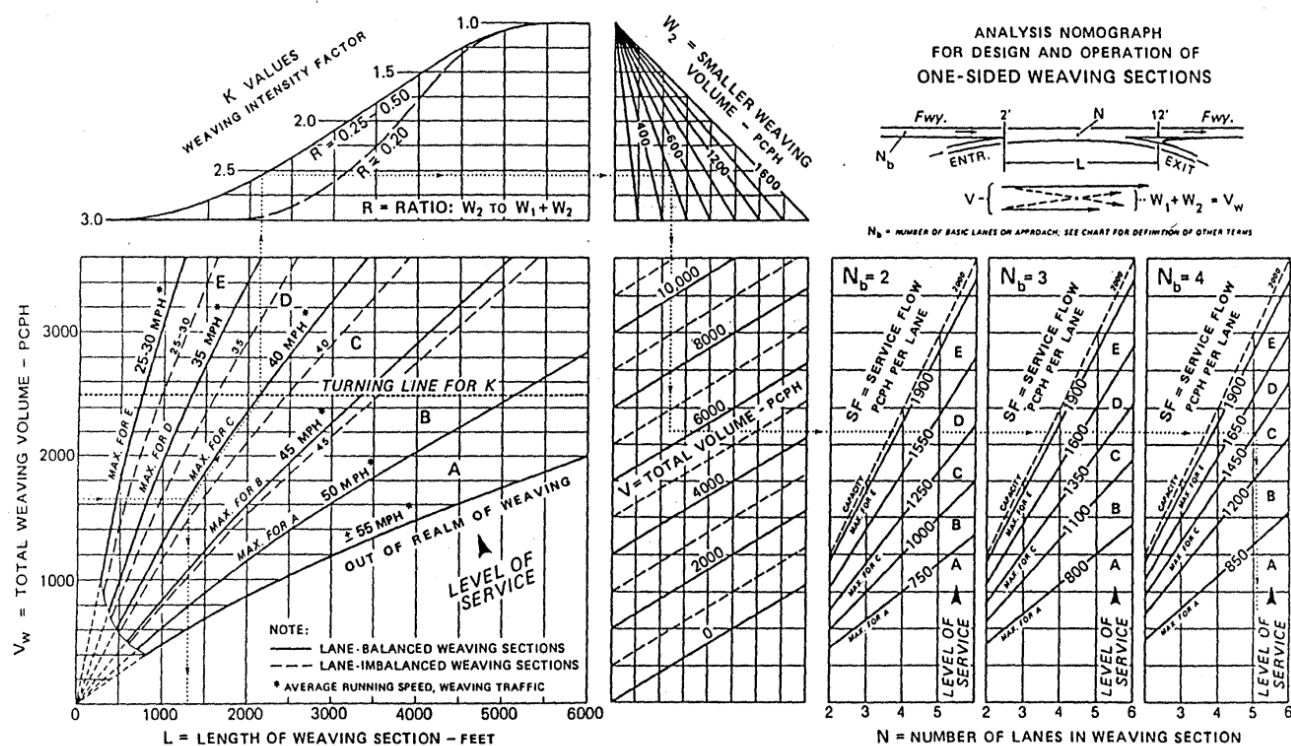


Figure 1. Leisch graphs for one sided weaving section lengths – source: [30].

There are other recommendations from several other state agencies but none of them specifies how the distance between the terminal intersection and the first intersection impacts lane changing on urban arterials near interchanges.

### Left Turning Vehicles

Vehicles that enter the arterial from the freeway off ramp and intend to turn left at the next intersection can impede arterial through traffic [23]. Messer and Bonneson, who classified arterial weaving maneuver types, determined that left turning vehicles have the most potential for impacting traffic flow speed due to the increased associated number of decelerations, accelerations, and weaving periods [31]. Table 1 shows Messer's and Bonneson's classification of an arterial weaving section. This table shows that paths number 1 and 2 were classified as weave type 1, which were the most difficult weaving type per the authors' definition. The left-turning vehicles follow path 1 on the arterial segments studied in this research.

Table 1. Classification of Lane Change Maneuvers Present at an Urban Arterial near an Interchange –  
Source: [31]

Path No.	Maneuver (Entry to Exit)	Weave Type	Turns Made	Lane Changes	
				2 Lane	3 Lane
1	Right Turn to Left Turn	1	2	1	2
2	Left Turn to Right Turn	1	2	1	2
3	Right Turn to Inside Through Lane	2	1	1	2
4	Left Turn to Outside Through Lane	2	1	1	2
5	Inside Through Lane to Right Turn	2	1	1	2
6	Outside Through Lane to Left Turn	2	1	1	2
7	Through to Adjacent Through Lane	3	0	1	1 or 2
<b>Type 1: Maximum Difficulty, Type 3: Minimum Difficulty</b>					

### Right Turning Vehicles

The American Association of State Highway Transportation Officials' (AASHTO's) A Policy on Geometric Design of Highways and Streets, commonly known as the Green Book, recommends providing right turn lanes to arterial streets in order to remove decelerating vehicles from through lanes [32]. The Green Book recommends different right turn lane lengths based on design speed. Several studies have investigated the impact of right turning vehicles and the necessity of adding auxiliary right turns at intersections. Alexander used regression to calculate delay experienced by through vehicles [33], including 12 variables: grade, width, volume, percentage of right turning and left turning traffic, v/c values, and location (urban vs rural). He concluded that the approach volume, right turning volume and average speed of non-delayed through vehicles were the main factors contributing to the total delay. The following equation shows Alexander's regression model.

$$SDH = -219.0 + 2.05X_5 + 0.37X_2 + 1.94X_6 \quad (3)$$

Where:

- $X_2$  = Approach Volume, vehicle per hour,
- $X_5$  = Number of right turning vehicles in approach direction per hour, and
- $X_6$  = average speed through the study area for a non-delayed through vehicles, feet per second.

McShane [34] used simulation to study the impact of right turning vehicles on speed of through traffic, including the following variables: main road volume, driveway volume, access density, location of access points, number of access points, number of lanes, and free flow speed on the main road.

## Driveway Entrance Speed

Stover et al. (1970) showed that when the driveway entrance speed was increased from 2 mph to 10 mph, through vehicles experienced less delay [35]. The experienced reduction in delay was also related to through volume per their study. Figure 2 represents a proposed graphic developed by Stover et al. (1970).

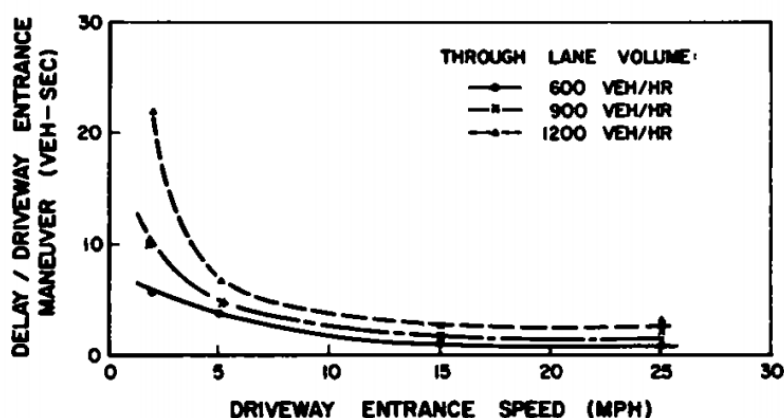


Figure 2. Relationship between delay and driveway entrance speed. – source: [35]

## Access Density

Several researchers have studied the relationship between access density and travel time. Reily et al. studied access density on freeways and observed that, for high volume driveways (> 600 vehicles per hour), the introduction of driveways adversely impacted the through traffic speed [36]. McShane conducted a similar study for and observed drops in free flow speeds as number of driveways per mile increased [34].

The HCM suggests a reduction in free flow speed on highways based on the number of access points [27]. Table 1 is a table from the HCM showing a reduction in free flow speeds based on access point density.

Table 2. Reduction in Free Flow Speed on Highways Based on Number of Access Points. – Source: [27]

Access Points / Kilometer	Reduction in Free Flow Speed (km/h)
0	0.0
6	4.0
12	8.0
18	12.0
≥ 24	16.0

The Oregon DOT Highway Design Manual suggests allowing only right in/right out access to private properties along urban highways [37] but does not quantify the impact of access points on the safety or operation of traffic on the transportation network.



## Median Treatment

The importance of median treatment on the operational performance of traffic has been well documented. Several guidelines suggest or require non-traversable medians on urban arterials. For example, the Oregon DOT Highway Design Manual [37] states that:

Non-traversable medians are required on all new, multi-lane urban or rural expressways on new alignment. All other existing urban expressways should consider construction of a non-traversable median when projects are developed along these highways.

The Highway Design Manual further states, “The 1999 Oregon Highway Plan requires the construction of a non-traversable median for.... Modernization of all rural, multi-lane expressways, including statewide (national highway system), regional- and district-level roadways require non-traversable medians.” [37]

NCHRP Report 93 [35] suggests that when median openings are present, they should provide for a “natural” path for vehicles using the median to make turning movements. The guideline suggests using a bullet nose design for median openings since this minimizes the encroachment on the adjacent lane. NCHRP Report 93 also suggests minimum distances between several median openings based on arterial speed. These distances were calculated based on a 10 mph difference between through and turning vehicles and a deceleration rate of 8 ft/sec<sup>2</sup>. Table 3 lists minimum distance values for different arterial speed values.

Table 3. Minimum distances between median openings. – source: [35]

Arterial Speed	Minimum Distance(ft) *	
Arterial Speed	a	b
25	140	390
30	190	370
35	240	460
40	300	530
45	360	670
50	430	780
55	510	910
* +25 ft per each stored car a: 8ft/sec <sup>2</sup> deceleration rate with 10 mph deceleration in through traffic lane b: 6.5 ft/sec <sup>2</sup> deceleration rate with no deceleration in through traffic lane		

### Corner Clearance (First Driveway)

According to AASHTO's Green Book [32], designers should refrain from placing driveways within the functional area of an at-grade intersection. The functional area of an intersection has been defined for upstream segments of the intersections, but there are not enough guidelines for downstream segments of the intersections. In this study, the distance of the first driveway to the upstream intersection was included among the independent variables.

### Simulation

Simulation is considered an operation research and management technique and is widely used in conducting research. The first step in conducting simulation is building a model. In transportation engineering, simulation models are constructed by generating vehicles, assigning routes to vehicles [38–41], and assigning behaviors, such as lane change preferences, to drivers [16, 42–44] as well as building and modifying infrastructure and environmental properties of the ambient environment.

Simulation models rely on stochastic processes to generate random numbers and then use these numbers to construct the simulation models. Different random seeds generate different random numbers and, consequently, model outputs may differ from each other in different iterations. For this reason, each scenario is run several times with different random seeds. Determining the number of runs is important and serves two main purposes:

- Making sure enough runs have been executed to reach results with confidence, and
- Avoiding too many runs, which may result in wasting resources.

The goal of determining the number of simulation runs is to ensure that the study outputs are consistent and that different iterations yield similar results [45].

There are two major approaches to determining the number of necessary simulation runs [46][47]. The first set of techniques involve conducting a reasonable (within the study field) number of runs, calculating mean and standard deviation and using confidence intervals and margin of error formulas to calculate the required number of simulation runs.

The second set of techniques start with very few simulation runs (as few as two), which are then used to calculate mean, standard deviation, and the margin of error at each step. More simulation runs are then made until the desired margin of error is reached. In the present study, the authors used the first approach and incorporated engineering judgement to determine the final number of runs.

In this study, the confidence interval method was used. Rearranging the confidence interval formula gives the following equation for the number of required runs:

$$n = \left\lceil \frac{SD^2 t_c^2}{\epsilon^2} \right\rceil \quad (5)$$



In equation 7  $\lceil \cdot \rceil$  represents the ceiling function and  $\varepsilon$  denotes allowable percentage error of the estimate. SD is the sample standard deviation and  $t_c$  is the critical value for the t distribution based on confidence interval. Like the confidence interval calculation, the researchers treated simulation runs as samples. To determine the appropriate number of simulation runs, the research team ran the simulation multiple times and based on the model outputs, calculated a new minimum number of simulation runs. This resulted in a small number of calculated required runs (less than four) since the models produced stable outputs. The research team included additional iterations and ultimately ran simulation ten times. Each simulation run was for one-hour worth of real-world conditions.

## Model Validation

Simulation models are built to serve specific purposes and each model should accurately serve the purpose for which it was designed. The evaluation of a simulation model's accuracy should reference its purpose, which should be clear before validation begins [48–50].

The first step in building each model is constructing its conceptual model. The conceptual model “is the mathematical/logical/verbal representation” of the study's subject [49]. Sargent defined the conceptual model validity as the process during which the modeler makes sure the assumptions and theories of the simulated models are correct and the simulation model represents the subject of the study. The second step in simulation is to build a computerized model. A computerized model unifies different elements of the conceptual model into one model that can represent the study subject.

To ensure a model's accuracy, researchers verify and validate models. Verification involves checking to make sure the conceptual model has been accurately converted to the computerized model [51]. No model can reflect the actual situations with absolute accuracy because even the collected data and the mathematical models underlying the models may have inherent errors. Accordingly, in verifying the model, modelers ensure that the model is “sufficiently accurate” [50].

Many researchers propose that each stage of model building requires some form of verification or validation parallel to the model building task to ensure satisfactory outcome. Different researchers classify validation tasks into different groups, but most acknowledge three distinct categories: conceptual model validation, data validation, and operational validation. Conceptual validation is conducted before comparing simulation results and is mainly intended to ensure that the simulation is capable of supporting its intended uses [52]. Data validation ensures that the quality and accuracy of input data is satisfactory. Operational validation compares the outputs of simulation to real world conditions to verify that the model can mimic the intended operation. Robinson [50] divides operational validation into “white-box” and “black-box” validation. White-box validation deals with the operation of small segments of the model, while black-box validation ensures that the whole model is representative of the real world with regard to the purpose of the study. In the

context of the present study, where the performance was “observable,” a hypothesis test was suggested to compare the output of the model to the respective observed values.

A wide range of statistical tests are used for hypothesis testing. The t-test is often used in validating simulation models. Sargent proposed adding another step after performing the t-test to account for the range of a model’s accuracy [48]. Other recently developed validation models have studied validation methods for agent-based models [53] and used versions of hypothesis testing to compare model outputs to real world data.

Researchers should choose validation techniques based on available data, the properties of their model, the and purpose(s) of their study. If there are multiple observations of a system, it is possible to use statistical validation approaches, such as hypothesis testing. On the other hand, if there is only one system observation, confidence intervals are more commonly used [54].

### Independent Samples T-test

The independent samples t-test compares two sets of data points to determine if they are significantly different from each other. This method was first developed by William Gosset in 1908 and has been widely used since then [55]. The t-test is categorized as a hypothesis test where the null hypothesis is that the mean values of the two sets are not significantly different from each other.

The concept of the t-test is to determine whether the measured difference between two samples is smaller or larger than the standard error of the difference between the mean values of the two study samples [56]:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S_{\bar{X}_1 - \bar{X}_2}} \quad (6)$$

- where  $\bar{X}_i$  is the mean for sample i.

$S_{\bar{X}_1 - \bar{X}_2}$  is the standard error of the difference between the means of the two samples:

$$S_{\bar{X}_1 - \bar{X}_2} = \sqrt{S_{\bar{X}_1}^2 + S_{\bar{X}_2}^2} \quad (7)$$

- where  $S_{\bar{X}_i}$  is the standard error of the mean for sample i, and

$$S_{\bar{X}_i} = \frac{SD}{\sqrt{n}} \quad (8)$$

where:

- $SD$  is the standard deviation of the sample and
- $n$  is the sample size.

In the present study, travel times were measured multiple times using a GPS enabled device in a pilot vehicle. This allowed us to calculate the mean and standard deviations of the real measurements and compare them to similar measures of output data. The independent sample t-test will be used to validate the models based on travel time. In conducting a t-test, it is assumed that the data points were obtained from a normal distribution.

### Confidence Interval Approach

A confidence interval is a range of computed values [57] and is computed based on the mean of the measurements, level of confidence, sample size, and standard deviation of the population or of the sample. The confidence interval is written as [L,U], where L represents the lower bound and U represents the upper bound:

$$\text{Confidence interval} = \left[ \bar{x} - z_c \frac{\sigma}{\sqrt{n}}, \bar{x} + z_c \frac{\sigma}{\sqrt{n}} \right] \quad (9)$$

where  $\bar{x}$  is the sample mean,  $z_c$  is the critical value for normal distribution for confidence interval  $c$ ,  $\sigma$  is the standard deviation of the population, and  $n$  is the sample size. In cases where the population standard deviation is not known, it is estimated based on the sample standard deviation. In this case, the standard z distribution is replaced by student t distribution:

$$\text{Confidence interval} = \left[ \bar{x} - t_c \frac{s}{\sqrt{n}}, \bar{x} + t_c \frac{s}{\sqrt{n}} \right] \quad (10)$$

where  $s$  is the sample standard deviation and  $t_c$  is the critical value for the t distribution based on confidence interval  $c$ . The values for  $z$  and  $t$  can be calculated and are available in statistical tables. Different degrees of freedom yield different  $t$  values. shows the  $z$  and  $t$  values for commonly used confidence levels.

Table 4.  $z$  and  $t$  values for commonly used confidence levels.

Confidence Level $c$	Normal $z$	Student $t$	Student $t$	Student $t$	Student $t$
<b>0.8</b>	1.282	1.476	1.372	1.325	1.310
<b>0.9</b>	1.645	2.015	1.812	1.725	1.697
<b>0.95</b>	1.960	2.571	2.228	2.086	2.042
<b>0.99</b>	2.576	4.032	3.169	2.845	2.750

The number of lane changes are measured based on the recorded video files, and thus there is only one measurement of the number of lane changes for each study site. Using a confidence interval approach, a margin of error for the output of the simulation is calculated and the real world measurements are checked to determine if they are within a confidence interval.

To validate the number of lane changes, the authors assume the data from video files to be the ground-truth-value of the lane changes ( $\mu_0$ ) and conducted a confidence interval testing to see if the  $\mu_0$  value is in the 99% confidence interval of simulation results.

Using a confidence interval approach, the authors calculated a margin of error for the outputs of the simulation and examined the real-world measurements to be within a confidence interval for each Segment..

## Linear Regression

Regression analysis is one of the oldest analysis methods in modern mathematics, with the first publications dating back to 1805 [63]. Among different statistical data modeling techniques, multiple regression analysis is considered very powerful and is capable of conveying meaningful clues about the relationship between each of the explanatory (independent) variables on the response (dependent variable) when other variables are assumed constant. This technique helps determine the impact of each of the study variables on the outputs of the simulation models.

Conventionally, a simple multiple regression analysis is used when there are multiple independent variables to predict the response. The following section explains this concept further.

A multiple linear model has the following functional form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_r X_r + \varepsilon \quad (11)$$

where  $X_i$  represents each independent variable and  $\beta_i$  quantifies the relationship between  $X_i$  and  $Y$ .

Coefficients  $\beta_i$  are usually calculated in such a way that the resulting equation yields the minimum sum of squares of the errors for each data point. After calculating the coefficients, the next step is making the decision as to whether the variable  $X_i$  should be included in the final model. This is done by conducting a hypothesis test for each variable, with each null hypothesis being “if the coefficient for the variable  $X_i$  is equal to zero.” To test this hypothesis, a p-value is calculated; this value is equal to the probability that the null hypothesis is true. A small p-value indicates that there is reasonable evidence in the data that supports the alternative hypothesis. The alternative hypothesis indicates that there is a relationship between the variable and the response when other variables are assumed constant. The choice of the boundary for the p-value is chosen by the researchers rather than based on calculation. Usually, a 0.05 value is chosen for the p-value, indicating that variables with p-values less than 0.05 should be considered statistically significant.

Each  $\beta_i$  estimates the magnitude of influence that each independent variable has on the response. Selecting the most significant independent variables and determining their respective  $\beta_i$  are the main contributions of this study. The  $\beta_i$ s help determine which factors impact fluctuation in the number of lane changes. The relationships developed in this study can help planners and engineers determine the magnitude of impact of each variable on lane changes.

## Variable Selection

Variable selection is an important step in building statistical models such as linear regression. Stepwise selection methods (including forward and backward selection) have been traditionally

used in selecting the final variables. The forward selection method starts with an empty model (no variables or predictors) and in each step adds one model variable. In each step, the variable that best improves the model is added. In the backward selection method, the first model includes all variables and in each step the variable that is least useful is removed from the model. There are also hybrid approaches that use a combination of forward and backward selection methods to build the best model. These methods are employed to create several models, each with a different number of variables. Measures such as Mallows' Cp, Akaike Information Criterion, Bayesian Information Criterion and adjusted R2 are used to make the final model selection.

Shrinkage methods are more recently developed and have some advantages over stepwise selection methods. The stepwise selection methods estimate coefficients by minimizing the least squares:

$$RSS = \sum_{i=1}^n (y_i - \beta_0 - \sum_{j=1}^p \beta_j x_{ij})^2 \quad (12)$$

Shrinkage methods constrain or shrink the coefficient towards zero by penalizing larger coefficients. This means that coefficients have smaller magnitude while still making satisfactory predictions. Statistical models built with shrinkage not only work well on training data, they also work well with test data. Two common shrinkage methods are ridge regression and the lasso, which are described below.

The ridge regression estimates coefficients such that they minimize:

$$\sum_{i=1}^n (y_i - \beta_0 - \sum_{j=1}^p \beta_j x_{ij})^2 + \lambda \sum_{j=1}^p \beta_j^2 = RSS + \lambda \sum_{j=1}^p \beta_j^2 \quad (13)$$

Where  $\lambda \geq 0$  is a tuning parameter that determines the strength of the coefficients' shrinkage. The second term in equation 13 is called the shrinking penalty. When  $\lambda = 0$ , ridge regression is equivalent to the least squares method.

While ridge regression estimates small coefficients, it still includes all of the variables in the final model. The lasso method is a more recent alternative to ridge regression. This method forces some of the variables to be exactly zero when  $\lambda$  is large enough [64]. The lasso minimizes:

$$\sum_{i=1}^n (y_i - \beta_0 - \sum_{j=1}^p \beta_j x_{ij})^2 + \lambda \sum_{j=1}^p |\beta_j| = RSS + \lambda \sum_{j=1}^p |\beta_j| \quad (14)$$

Since the lasso sets some variables to exactly zero, it can be used to perform variable selection. In this study, the lasso method was used for final variable selection.

## Method

The data used in this research was acquired from the NCHRP 07-23 project data. The preliminary data for NCHRP 07-23 report was collected using various resources, including videotaping and using a GPS-enabled pilot vehicle to collect travel time data. Volumes, origin-destination matrices,

lane-change data, and signal timing were all reduced from the video files. These data were used to construct, calibrate, and validate simulation models. Three sites in the vicinity of diamond interchanges were chosen as study sites. Diamond interchange setting is a common setting in the US. A diamond interchange has four one-way ramps between an urban arterial and the crossing freeway which make a diamond shape. Four intersections, including two terminal intersections and two adjacent signalized intersections, were modeled for each study site. Figure 3 illustrates a sketch of the models. Each study site consisted of four study segments (segments one to four in Figure 3).

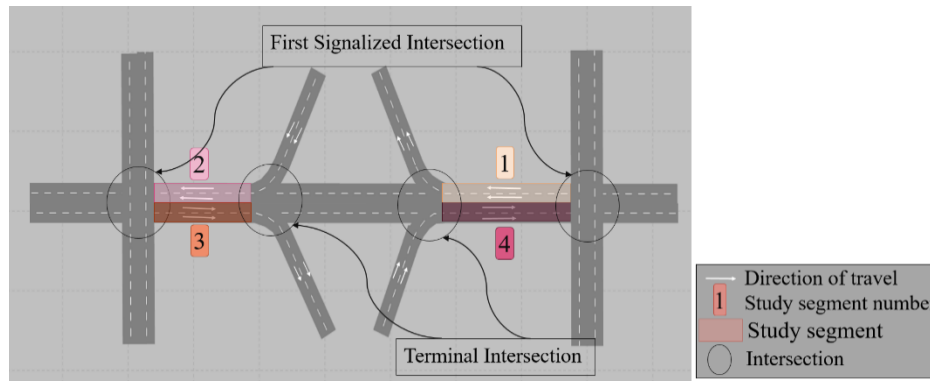


Figure 3 Simulation model sketch.

After building simulation models, four variables were chosen to manipulate and build different scenarios: volume, median option, right turning movement control type at the terminal intersection, and driveway settings. Table 5 summarizes the options that were used to build the simulation models. Option names are presented in parentheses.

Table 5. Scenario Settings Based on Different Options.

Volume	Driveway	Median	Right Turn Control
Off-peak (MV0)	No change (DW0)	No change (MED0)	Stop (OP0)
Peak (MV1)	One Driveway (DW1)	Raised (MED1)	Yield (OP1)
0.5*C (MV2)	No Driveways (DW2)	--	--
0.75*C (MV3)	--	--	--
Capacity (MV4)	--	--	--

The researchers conducted a full factorial study, meaning that all available variable options were combined with all other variable options to build scenarios. A Python program was developed to build scenarios and run the simulation software. PTV-Vissim simulation software was used to construct simulation models. The output files collected for this study included the following:

- **A vehicle records output file** that logged information about each vehicle in user specified intervals. The vehicle records data can be adjusted to research needs. For this study, the team collected vehicle number, simulation run, origin zone, destination zone, lane change, and delay every second. The vehicle records file was produced for each of the simulation runs. For example, for a site with 60 scenarios and 10 runs for each

scenario, 600 files were created. Each file contained data for all four study segments. Thus, a network with 60 scenarios contains information for about 240 study segments.

- **A lane change data file** that logged each lane change movement. The lane change output file cannot be adjusted to include user specified variables, logging only the vehicle number, link number, lane number, speed, acceleration, and leading and lagging vehicles information. A computer program was written in R to extract the needed data for each lane change movement in the lane change data file from the vehicle records output file. This file was produced for each of the simulation runs. For a study segment with 60 scenarios that each ran 10 times, 600 lane change data files were created.
- **Four travel time measurement segments** that logged travel time, number of vehicles, and simulation run number for each 15-minute interval in each run.
- **Data collection points right after each stop line** at each intersection that logged the number of vehicles passing that point at each simulation run.

In addition to the Vissim output data, team members used Google® maps to measure geometric design characteristics for inclusion in the analysis. The off-peak, peak, 50% of capacity, 75% of capacity, and full capacity volumes were considered in designing the scenarios. The peak and off-peak volumes were collected directly from the study sites. The capacities on the study segments were calculated based on the 2016 HCM and were distributed according to the peak conditions among main origins and destinations to match the capacity conditions. The 50% capacity and 75% capacity volumes were then calculated from the capacity origin-destination volumes. shows the collected variables for each of the study segments.

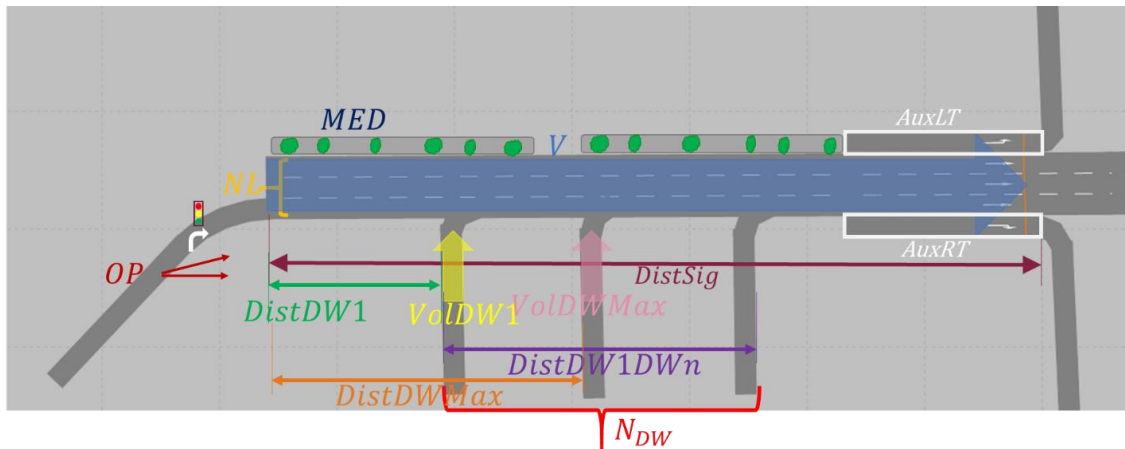


Figure 4. Collected design and operation variables for study segments.

The authors used the large amount of data that was created and applied analytical techniques to answer the research question. Running the large number of scenarios, collecting the corresponding data from the data collection points, output files, travel time output files, vehicle records output files, and lane change output files required big data management and analysis techniques.



As noted in the literature review, other researchers have used surrogate safety measures as a replacement for crash statistics. Here, the authors used number of lane changes as a measure of risk. Lane change numbers can be difficult to measure, but the abundance of collected data for this study allowed for constructing precise simulation models that could output number of lane changes. Team members validated the number of lane changes using the base condition simulation models and constructed different scenarios to account for different volumes, driveway settings, median openings, and right turning movements at the terminal intersection conditions.

The results shows that the number and location of lane changes are impacted by geometric design settings, and that number and location can be used to indicate risk on the roadways. Some factors, such as the location of medians, driveway settings, and signal configurations at the beginning of a segment can impact how and where vehicles change lanes.

After running simulation models, the number and location of lane changes at each study segment were recorded. Each study segment was divided into smaller subsegments. Choosing a homogeneous length for sub segments was considered and rejected due to the fact that the lengths of study segments varied between 430 and 1,310 feet. Choosing a short subsegment would be too short for the larger segments, while choosing a longer subsegment would cause precision problems in shorter segments. Subsequently, the team divided each segment into five subsegments of equal lengths, which allowed for the subsegment lengths to be relative to the segment lengths while keeping subsegment lengths in a reasonable range.

After extracting data for all subsegments, paired t-tests were conducted to investigate if the locations of lane changes were impacted by the different scenario settings. Since the numbers of lane changes were bound to the location, using the paired t-test provided the ability to match the number of lane changes to the location. After investigating whether the number of lane changes was impacted by the scenario settings, a statistical model was built to investigate the extent to which this variable impacted the location of lane changes.

The number of scenarios for each of the segments could be different due to the structure of the scenario management plan. For example, the two options for median were the “current median conditions” at the site and “all raised” median. Thus, for a study site with a raised median, the there would only be one median option.

The independent variables used in regression analysis were the following:

**AuxLt:** Binary variable, 1 indicates there exists an auxiliary left-turning lane, 0 if there are no auxiliary left turning lanes [No unit]

**AuxRt:** Binary variable, 1 indicates there exists an auxiliary right-turning lane, 0 if there are no auxiliary right turning lanes [No Unit]

**DenDw:** Density of the driveways [Driveway/mile]

**DistDw1:** Distance of the first driveway from the upstream intersection [feet]

**DistDw1DwN:** Distance of the first driveway to the last driveway [feet]



**DistSig:** Distance from upstream intersection to the first signalized intersection [feet]  
**DistUPSDwmax:** Distance of the upstream intersection to the largest volume driveway [feet]  
**DistUPSLTLane:** Distance of upstream intersection to the beginning of the left-turning lane (if no left-turning auxiliary exist, this is equal to DistSig) [feet]  
**DistUPSMed:** Distance of upstream intersection to the beginning of the first median opening [feet]  
**DistUPSRT:** Distance of upstream intersection to the beginning of right turning lane [feet]  
**DistUPST1LT:** Distance between upstream intersection to the first point where cars can turn left (can be a median opening or at the intersection, whichever is shorter) [feet]  
**LenMedStor:** Length of median storage [feet]  
**MdensDw:** Modified density of the driveways (number of driveways\*5280/distance from the start of the first driveway to the end of the last driveway) [Driveway/mile]  
**MedContin:** Binary variable, 1 if the median is continuous through the entire segment, 0 otherwise [No unit]  
**NL:** Number of lanes [Count]  
**NLC:** Number of lane changes [Count]  
**NoDw:** Number of driveways [Count]  
**NoLTLanes:** Number of exclusive left-turning lanes [Count]  
**NoMed:** Number of median openings [Count]  
**NoRTLanes:** Number of exclusive right turning lanes [Count]  
**SimVolLT:** Simulated left-turning volume passed through the downstream intersection [Vehicles/hour]  
**SimVolRT:** Simulated right turning volume passed through the downstream intersection [Vehicles/hour]  
**SimVolTru:** Simulated through volume passed through the downstream intersection [Vehicles/hour]  
**SimVolUT:** Simulated u-turn volume passed through the upstream intersection [Vehicles/hour]  
**TMed:** Median type (1= raised median, 2= raised median with median opening, 3= Two Way Left Turning Lanes) [Categorical]  
**TT:** Travel Time [Seconds]  
**VolDwmax:** Volume of largest volume driveway [Vehicles/hour]  
**WidthDw1:** Width of the first driveway [feet]  
**WidthDwMax:** Width of the largest volume driveway [feet]  
**WiMedOp:** Length of median opening [feet]

The dependent variable was flux as explained in Performance Measure Selection section. Since flux is a standardized measure, all data from all 12 segments (4 segments in each study site) were compiled into one data frame and were analyzed together.

# Results

## Descriptive Statistics

The authors studied three sites, each with four traffic segments. There were 60 scenarios for sites 1 and 3 and 30 scenarios for site 2. From these scenarios, a database with a total of 6,000 data points was built. Figure 5 shows the probability density plot for the CV values.

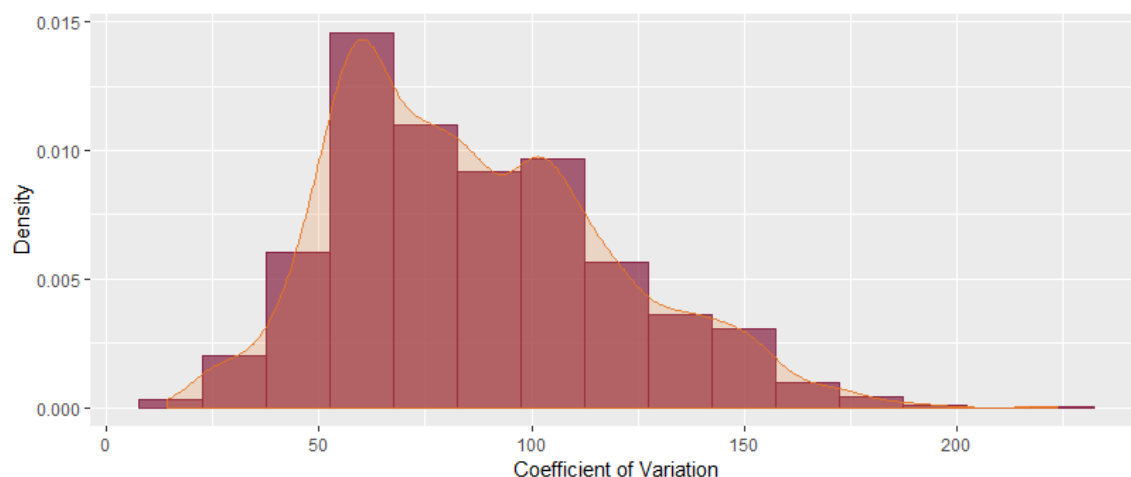


Figure 5. Density plot of CV for all segments.

Figure 6 shows histograms based on the segment characteristics. Segments one and three (odd segments) were located upstream of the terminal intersections while segments two and four (even segments) were located downstream of the terminal intersections.

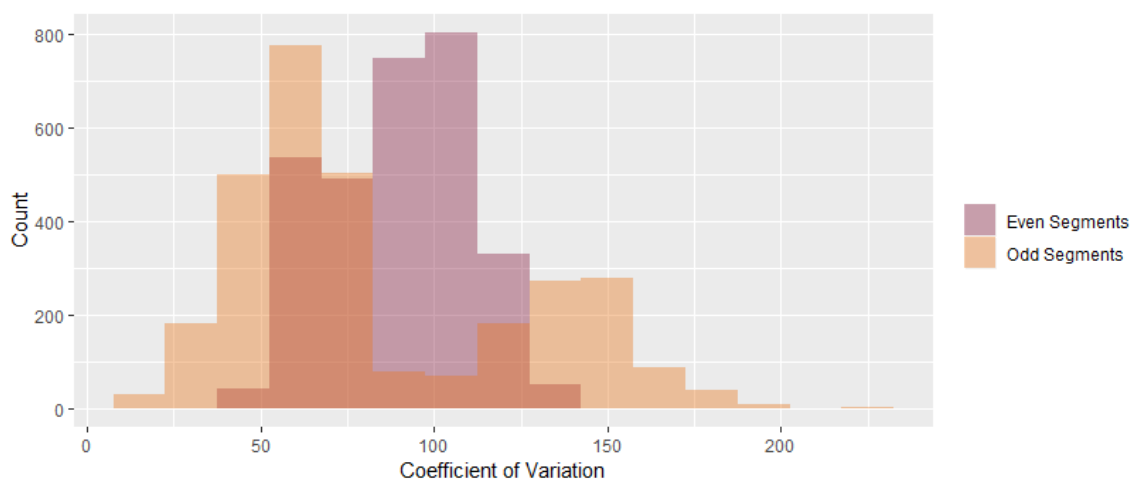


Figure 6. Histograms of coefficient of variation for even and odd segments.

Four boxplots were created to illustrate the difference between fluctuation values for different scenario variables. Figure 7 illustrates the box plots for different options of each of the scenario variables.

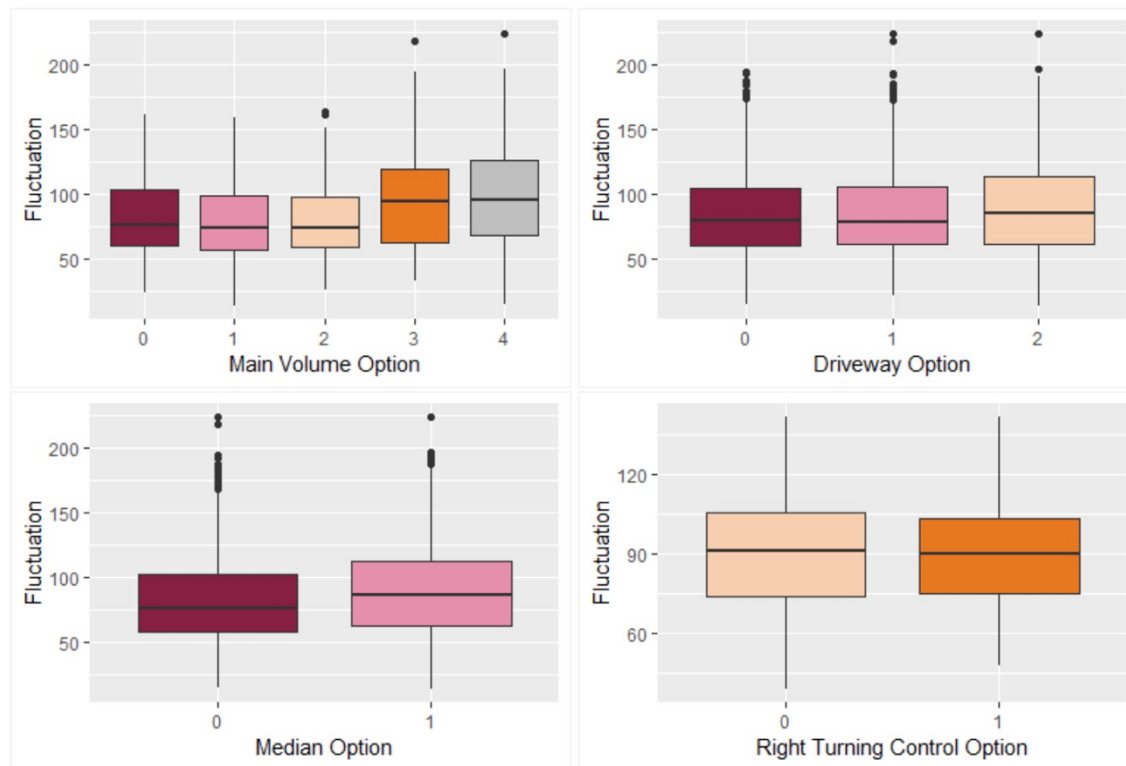


Figure 7. Scenario Options Boxplots.

## Paired t-tests

Before building statistical models, the research team investigated whether different scenario design options impacted the number of lane changes in the small subsegments. To achieve this goal, the main data set was divided based on scenario variables and then paired t-tests were conducted to see if changing an option impacted the number of lane changes. The authors used paired t-tests because the number of lane changes were distributed differently along each segment. The research team compared the number of lane changes in one subsegment by keeping all but one variable constant.

Table 6 shows the results of all paired t-tests. In all comparisons (each row) the null hypothesis ( $H_0$ ) was that the mean difference ( $\mu_d$ ) between the two sets was equal to zero. The alternative hypothesis ( $H_1$ ) assumed that  $\mu_d$  was not equal to zero.

Table 6. Paired t-test results.

Set 1	Set 2	t-Value	p-Value	Mean of the Differences
MV0	MV1	-61.182	< 2.2e-16	-26.78317
MV0	MV2	-52.964	< 2.2e-16	-83.3595
MV0	MV3	-30.017	< 2.2e-16	-41.6755
MV0	MV4	-26.658	< 2.2e-16	-59.79767
MV1	MV2	-43.477	< 2.2e-16	-56.57633
MV1	MV3	-11.165	< 2.2e-16	-14.89233
MV1	MV4	-14.903	< 2.2e-16	-33.0145
MV2	MV3	26.119	< 2.2e-16	41.684
MV2	MV4	9.8204	< 2.2e-16	23.56183
MV3	MV4	-14.322	< 2.2e-16	-18.12217
DW0	DW1	1.79	0.07253	0.6544
DW0	DW2	-0.15902	0.8737	-0.066
DW1	DW2	-1.7367	0.08248	-0.7204
MED0	MED1	46.336	2.2e-16	47.50242
OP0	OP1	-0.82589	0.4089	-0.05739015

The results showed that *volume* and *median* options had significant impact on the distribution of lane changes on study subsegments, while different *driveway* and *operation* options did not influence the number of lane changes in study subsegments. Since the p-values for different driveways were only slightly over 0.05 criteria, the authors chose to include these variables in the final statistical analysis models and investigate their impact.

Next, the authors built a regression model to investigate the impact of design variables on the study performance measure. The authors used lasso regression to conduct the regression analysis. Choosing the shrinkage penalty parameter (lambda) in the final model impacted the model's coefficients. Figure 8 shows R<sup>2</sup> scores for the models made with a range of 100 lambda values. The lambda producing the lowest cross-validation error was chosen as the best lambda, but the model with the lowest cross validation error included a larger number of independent variables (forced fewer coefficients to be exactly zero).

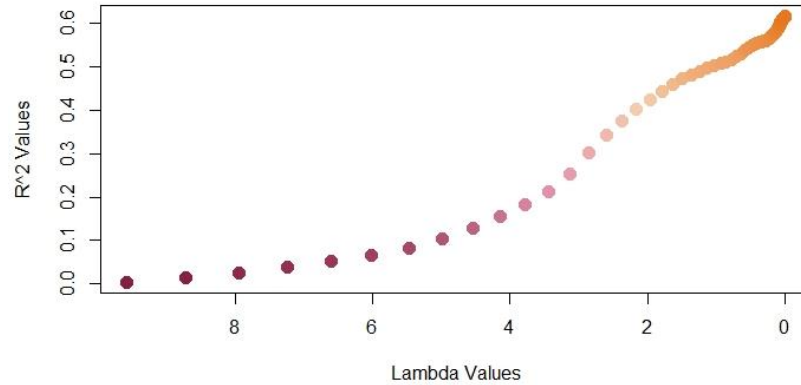


Figure 8. R2 scores for different lambda values.

Table 7 shows the 10 largest coefficients for the best lambda sorted from largest to smallest value. The  $R^2$  score for this model was 0.61 and it can be seen that “Section3” and “Section2” binary variables were among the independent variables with the largest coefficients. In the next step, the researchers separated the upstream and downstream segments and repeated the regression step.

Table 7. Coefficients table for the comprehensive model.

Coefficient	Value
(Intercept)	67.13
AuxLt	52.34
AuxRt	-50.73
Section3	28.18
NoDw	27.99
MedContin	-25.24
Section4	17.93
DensMedop	13.15
Section2	9.30
DenDw	-4.68
TMed2	-2.32

Segments 1 and 3 were located upstream of freeway on-ramps (upstream segments) and segments 2 and 4 were located downstream of freeway off-ramps (downstream segments). For upstream segments, Table 8 summarizes the coefficient values. The  $R^2$  score for this model was 0.75.

Table 8. Coefficients table for upstream segments.

Coefficient	Value
(Intercept)	53.63
AuxRt	27.70
NoDw	14.60

Coefficient	Value
Mden.Den	1.73
OP1	1.40
DenDw	1.00
VolDwmax	0.88
WidthDwMax	-0.80
NLCmeans	-0.64
MedContin	-0.41
MED1	-0.38

Table 9 summarizes the coefficient values for downstream segments. The  $R^2$  score for this model was 0.71.

Table 9. Coefficients table for downstream segments.

Coefficient	Value
(Intercept)	88.36
MedStor	37.20
AuxRt	-29.90
TMed2	4.77
NoDw	3.29
DW 1	1.17
OP1	-0.69
DW 2	0.44
DenDw	-0.44
VolDwmax	-0.27
WidthDw1	-0.19

## Discussion

Comparing  $R^2$  scores for the comprehensive model, the upstream model and downstream models showed that dividing the study segments into upstream and downstream groups improved the final model fitness. This made intuitive sense since the travel patterns in the two groups of segments are different. While the vehicles that exit the ramp and enter the downstream segments need to make more lane changes, and a large portion of them need to make a left turn at the first signalized intersection, vehicles on the upstream segments are not impacted as significantly by mandatory lane changes. After dividing the comprehensive data set into upstream and downstream groups, two regression models were built.

Table 10, 11, and 12 present the three models with the largest coefficients.

Table 10. Largest coefficients for the comprehensive model.

Coefficient	Value
(Intercept)	67.13
AuxLt	52.34
AuxRt	-50.73
Section3	28.18
NoDw	27.99
MedContin	-25.24
Section4	17.93
DensMedop	13.15
Section2	9.30

Table 11. Largest coefficients for downstream segments.

Coefficient	Value
(Intercept)	88.36
MedStor	37.20
AuxRt	-29.90
TMed2	4.77
NoDw	3.29
DW1	1.17
OP1	-0.69
DW2	0.44
DenDw	-0.44

Table 12. Largest coefficients for upstream segments.

Coefficient	Value
(Intercept)	53.63
AuxRt	27.70
NoDw	14.60
Mden.Den	1.73
OP1	1.40
DenDw	1.00
VolDwmax	0.88
WidthDwMax	-0.80
MedContin	-0.41

Equations 15 and 16 are suggested to model flux in urban arterials near diamond interchanges.

$$flux_{(down)} = 88.36 + 37.20 \times MedStor - 29.90 \times AuxRt + 4.77 \times Tmed2 + 3.29 \times NoDW \quad (15)$$

$$flux_{(up)} = 55.63 + 27.70 \times AuxRt + 14.60 \times NoDw + 1.73 Mden/Den \quad (16)$$

Providing an auxiliary right-turning lane helped alleviate the fluctuation on downstream segments, while it contributed to increased fluctuation on upstream segments. The number of driveways contributed to an increase in fluctuation on downstream segments with a much higher factor (14.60) than on upstream segments (3.29). On downstream segments, the length of median storage had the highest coefficient, which meant that providing median storage contributed to increased fluctuation at these locations. The results showed that Type 2 medians (raised with openings) increased fluctuation on the number of lane changes while they did not significantly impact fluctuation on upstream segments.

## Conclusions and Recommendations

The objective of this research was to understand the impact of design factors on traffic flow safety on urban arterials in the vicinity of interchanges. To achieve this objective, a safety performance measure was defined to determine the fluctuation in the number of lane changes on an urban arterial segment. This study hypothesized that lane change maneuvers decreased the safety performance of traffic on urban arterials near diamond interchanges and that, if they take place in close proximity to each other, the cumulative risk of a crash would increase significantly.

To model the distribution of lane changes on urban segments, each study segment was divided into five equal subsegments and the number of lane changes were measured on each subsegment. Coefficient of Variation (CV) is a statistical measure of fluctuation and is measured as the proportion of standard deviation and the mean. Since CV is a small number (usually between 0 and 1), the authors used  $100 \times CV$  (named flux in this study) as the measure of fluctuation in the number of lane changes on study segments. Flux was used as the dependent variable and collected design variables were used to build statistical models. The preliminary analysis showed that dividing study segments into upstream and downstream improved the accuracy of the statistical model. As a result of the preliminary analysis, two models were built to formulate the flux with respect to design variables.

The results show that, for upstream segments, providing a right turning lane increased the fluctuation in the number of lane changes. This meant that when a right turning lane was present in upstream segments, lane change maneuvers were accumulated in one subsegment of the road. Moreover, the number of driveways increased the fluctuation. For each added driveway, the flux increased by 14.6, which meant that providing fewer access points could improve safety in upstream segments of urban arterials.



A new variable was added to account for how closely driveways were located on study segments. Modified density was defined as the number of driveways in the distance between the beginning of the first driveway to the end of the last driveway. This variable is always larger than or equal to the traditional driveway density (number of driveways in the entire segment). The proportion of modified density to density was used as a measure of driveway proximity. This variable was of the variables with a large coefficient in the upstream flux model, which meant that spreading access points along a roadway was preferred over providing several access points in a short distance.

For downstream segments, providing right turning bays decreased flux, which meant that providing a right turning lane could improve the safety performance of traffic flow on urban arterials located downstream to the terminal intersection.

Having a median storage was the variable with the largest coefficient for downstream segments, which meant that raised medians with median openings that provided median storage negatively impact the safety performance of urban arterials downstream to the terminal intersection. Tmed2 was another variable in the model that referred to a raised median with openings. These results indicate that if it is necessary to provide access to the opposing side of a road, having two way left turning lanes is superior to building raised medians and providing median openings.

## Additional Products

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### Education and Workforce Development Products

NA

### Technology Transfer Products

Presenting at the UTC Student Leadership Development Seminars Series, October 10, 2019

### Data Products

NA

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