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Congestion Mitigation Strategy: Modeling the Effect of Different Geometric Configurations of a Two-Lane On-Ramp on Capacity Using VISSIM

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CONGESTION MITIGATION STRATEGY: MODELING THE EFFECT OF DIFFERENT GEOMETRIC CONFIGURATIONS OF A TWO-LANE ON-RAMP ON CAPACITY USING VISSIM

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CONGESTION MITIGATION STRATEGY: MODELING THE EFFECT OF DIFFERENT GEOMETRIC CONFIGURATIONS OF A TWO-LANE ON -RAMP ON CAPACITY USING HCS2010 AND VISSIM

RHIZLANE BRACHMI

ABSTRACT

Freeway on-ramps are critical components of freeway systems since they control the entry of traffic to the mainline. According to the Highway Capacity Manual (HCM), a two-lane on-ramp configuration will achieve less turbulence than a similar one-lane on-ramp but little guidance on the desired lengths of the acceleration lanes or their effect on the operation of the influence area is provided.

An experiment was designed to investigate the effect of the lengths of the acceleration lanes of isolated, two-lane on-ramps on the operation of the ramp influence area. The Highway Capacity Software (HCS) was used to calculate the density of the influence area corresponding to five length combinations for the first and second acceleration lanes, L_{A1} and L_{A2}, keeping the effective length, L_{Aeff} constant. The analysis was carried out using two sets of volumes for the freeway, V_F and ramp, V_R. As expected, the density of the ramp influence area remained constant, for each volume set, illustrating that the HCM methodology is not sensitive to changes in the acceleration lane lengths making up L_{Aeff}.

The experiment was repeated using the microscopic traffic simulation software, VISSIM. As expected, the two-way ANOVA results indicated the effect of the volume was significant (($p<0.001$, $\alpha=0.05$). As, L_{A1} decreased from 500ft to 100ft and L_{A2} increased from 500ft to 1300ft, the average density in the ramp influence area decreased when V_f=5000vph and V_r=1000vph. This effect was found to be significant (p=0.029,

α=0.05) using a one-way ANOVA. However, the effect of the acceleration lane length was not significant (p=0.992, α=0.05) when V_F=3500vph and V_R=500vph.

These results raise questions about the HCM equation for estimating the density of the influence area for two-lane on-ramps. Possible changes to the HCM equation are discussed.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Freeway on-ramps are one-directional segments of roadway, which provide an exclusive connection to a freeway facility. Ramps may be used to connect one freeway to another or connect a hierarchical lower level roadway, such as a rural highway or urban arterial to the upper level freeway. The distance along which the ramp runs parallel to the mainline lanes, from the ramp nose to the tapered lane drop is referred to as the acceleration length. Acceleration lanes are designed to enable vehicles entering a roadway to increase their speed to a rate at which they can safely merge with through traffic (HCM, 2016). A two-lane freeway on-ramp is characterized by two separate acceleration lanes, each successively forcing merging maneuvers to the left (HCM, 2016). If the ramp has two lanes, the length of each acceleration lane is defined. The length of the first acceleration lane, L_{A1} is measured from the nose to the lane drop of the outer lane. The length of the second acceleration lane, L_{A2} is measured from the lane drop of the outer lane to the lane drop of the inner lane. The general configuration of a two-lane on-ramp is shown on Figure 1. To date, there is no guideline on how to best choose the lengths of the acceleration lanes of two-lane entrance ramps.

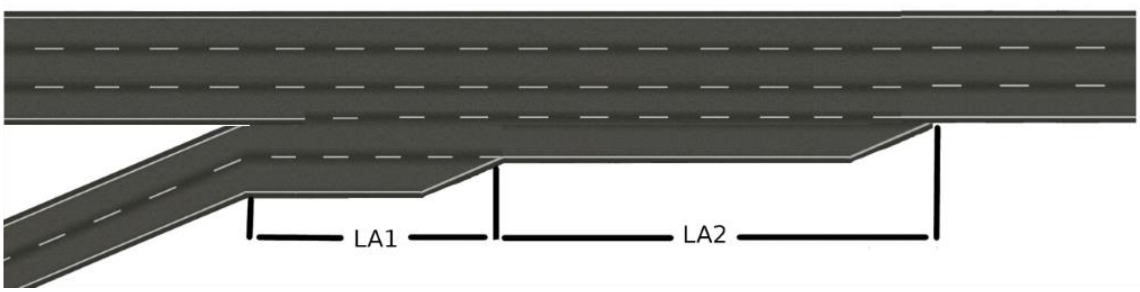

Figure 1. General Configuration of the Acceleration Lanes for a Two-lane On-ramp.

Ramps are designed to allow vehicles to merge at high speeds with minimum disruption to the traffic stream on the mainline. High-speed merging is achieved through a small difference in design speed between the ramp and the freeway (Shin et al, 1993). The length of the on-ramp provides vehicles entering the freeway space to accelerate before merging with freeway traffic.

Conflicts usually occur when two traffic streams compete for the same space. Such is the case when the traffic on the on-ramp must merge with the traffic on the freeway mainline. Since acceleration lanes are designed to allow road users to perform a safe merge, a better understanding of the design components, such as length and its effect on merging is crucial for highway and traffic engineers.

The traffic near an on-ramp usually experiences turbulence as the vehicles from the on-ramp merge with the vehicles on the mainline. The turbulence is seen as a local increase in density as vehicles bunch together and slow down. The turbulence is expected to increase with the volume of traffic on the ramp, the volume of traffic on the mainline of the freeway, and the number of lane changes vehicles make on the mainline.

Data quantifying the relationship between the lengths of the acceleration lanes and the density in the merge area is very scarce. According to the Highway Capacity Manual (HCM), the flow in the outer freeway lanes, lanes 1 and 2, immediately upstream of the on-ramp is generally somewhat higher for two-lane on-ramps than that for one-lane on-ramps in similar situations, and densities in the merge area are lower (2016). This area of turbulence is commonly referred to as a bottleneck and under high traffic demands the increase in density will propagate upstream, resulting is an area of congestion.

Americans spend 14.5 million hours every day stuck in traffic, trying to commute, or move goods to market (Morgan, 2018). Since 1970 the U.S. population has grown by 32% and the vehicle miles traveled has grown by 131%. However, the total number of road miles has grown by only 6% (Morgan, 2018). This imbalance between the growth in travel demand and the growth in infrastructure has led to an increase in the severity and duration of traffic congestion, which impacts many aspects of life.

Congestion occurs when demand exceeds the capacity of a roadway segment. In the case of an on-ramp and freeway merge segment, the traffic flow on both the on-ramp and the freeway mainline contribute to the demand but the capacity in the influence area is reduced because of the merging that is required. When such a merge area becomes congested, the road users experience decreases in travel speed and increases in travel time.

In addition, vehicles stuck in congestion produce greater tailpipe emissions, including carbon monoxide (CO), carbon dioxide (CO_2) and volatile organic compounds. These compounds degrade air quality and can have profound effects on public health.

According to Ciccone et al. (1998), the odds for asthma and a number of other asthmatic symptoms increase significantly in areas with heavy traffic flow.

Reducing congestion can therefore improve the travel experience for road users and improve air quality. A better design for two-lane on-ramps could help to reduce the stop-and-go traffic that occurs routinely near entrance ramps, which in turn could help alleviate some of the drawbacks of congestion.

1.1 Research Question

According to HCM, the turbulence near an on-ramp can be reduced by increasing the number of lanes on the on-ramp. It is expected that a two-lane ramp will provide less turbulence than a single-lane ramp. However, no guidance is provided as to the desired lengths of the acceleration lanes in either case. Therefore, the guiding research question is; what is the estimated impact of changing the lengths of the acceleration lanes on the operation of the ramp influence area?

1.2 Scope

The guiding research question could be construed as being quite broad, as the operation of a freeway segment is subject to changes in the traffic demand on the mainline and ramp, the behavior of the drivers, and the prevailing roadway and environmental conditions. This thesis was specifically focused on the impact of the lengths of the acceleration lanes on the mainline traffic operations. The lengths of the first and second acceleration lanes were varied while maintaining a constant effective length. The mainline and on-ramp traffic volumes were varied to improve the generalizability of the results. All other factors were not considered.

The analysis of the impact of the lengths of the acceleration lanes was limited to existing analysis methods, specifically a deterministic analysis using the procedures of the Highway Capacity Manual and associated Highway Capacity Software, and a stochastic microscopic simulation analysis using VISSIM, which serves as the state of the practice for transportation professionals.

1.3 Research Objectives

The purpose of this thesis was to investigate the effect of varying the lengths of the acceleration lanes of a two-lane on ramp on the operations of the ramp influence area. To achieve this purpose, the objectives are to:

1. Examine whether the deterministic analytic procedures of the Highway Capacity Manual and associated Highway Capacity Software predict a change in the density of the influence area under changes to the acceleration lane lengths; and
2. Examine whether a stochastic, microscopic traffic simulation model predicts a change in the operation of the influence area when the lengths of the acceleration lanes are changed.

1.4 Organization of the Thesis

This thesis is presented in six chapters. Chapter I includes an introduction of the topic and its importance and defines the research question and objectives. Chapter II provides a historical account of how the Highway Capacity Manual methodology has changed, from 1950 through to 2016. Chapter III covers the experimental design and the development of the HCS and VISSIM models. Chapter IV contains the results from the deterministic HCS analysis and the VISSIM model simulations, along with the conclusions drawn from those results. Chapter V covers a discussion of the results as they pertain to the current

HCM equation for estimating the density in the influence area, the contribution of this thesis, and thoughts about future work.

CHAPTER II

LITERATURE REVIEW

Understanding the effect of on-ramps on the operation of freeway merge areas is a relevant topic. The Transportation Research Board recently released a National Cooperative Highway Research Program (NCHRP) request for proposal to develop methodologies to update the HCM analysis procedures related to freeway merging, diverging, and weaving. In the project description, it was recognized that the procedures in the HCM are based on limited field collected data from over 25 years ago and that there now exists new datasets, collected through various roadway sensors, which may be used to improve these procedures.

2.1 The Highway Capacity Manual

The HCM is published by the Transportation Research Board (TRB) of the National Academies of Science. Changes to the publication are informed by research carried out through the National Cooperative Highway Research Program, Transit Cooperative Research Program and other federally funded research programs. The research results are reviewed by research panels and subcommittees of TRB’s Highway Capacity and Quality of Service before being considered for inclusion into the HCM.

The HCM represents the state of the practice for transportation engineers and as such, the procedures for analyzing freeway facilities, segments, merging and diverging areas have changed since the first edition of the HCM, published by the Bureau of Public Roads (BPR) in 1950.

2.1.1 1950 HCM.

2.1.1 1950 HCM. As the first HCM, the 1950 publication was largely focused on drawing the factual, technical data contained within previously published documents and new data developed through various investigations, including traffic operations research conducted by the Bureau of Public Roads, State highway departments and other government agencies. The previous published documents were rather scarce in terms of technical data because prior to 1934, obtaining factual data had been hindered by the lack of field instrumentation. With the development of suitable data collection tools, traffic operations research led to a better understanding of the characteristics of traffic flow.

Part VII Ramps and Their Terminals of the 1950 HCM included a section on conditions affecting ramp capacity. The more important and potentially controlling factors were identified as the volume of traffic using the facility that the ramp connects to, the weaving distance between ramps, and the conditions of the ramp terminals. It was recognized that the merge behavior, specifically the acceptance of gaps, affected the ramp capacity. It was also recognized that the distribution of traffic on the mainline changed depending on the traffic condition. Under low flows, drivers on the mainline tended to move from the outer lane to the inner lanes, thus avoiding interaction with the on-ramp traffic flow; while under high flows, the distribution across the mainline lanes became nearly balanced. Ramp capacities for a few specific locations were provided. These locations did not have acceleration lanes (HCM, 1950).

The 1950 HCM did not include any methodology to calculate the capacity of merging and diverging areas. Nor did the manual include any sample problems to illustrate how to analyze merge and diverge sections.

2.1.2 1965 HCM and 1985 HCM.

In the 1965 HCM Special Report 87, a complete methodology for ramps and ramp junctions was presented based upon the work of Joseph Hess of the Bureau of Public Roads (BPR). The main finding in this edition of the HCM was that the most critical element to evaluate an entrance ramp was estimating the lane 1 volume at merging areas.

A general procedure was provided for service volumes for levels of service A through C and an alternate procedure was provided for service volumes for levels of service D and E. Five worked problems were included illustrating how to apply the procedures.

The general procedure was described in terms of the following five steps.

1) Establish the geometry of the study location, including the number of freeway lanes and details about adjacent ramps.
2) Establish the demand volumes for the freeway and ramps.
3) Based on the geometry of the study location, select the appropriate equations to compute the volume on lane 1 of the freeway. The equations were also given as nomographs for the various ramp geometries.
4) Add the ramp volume to the computed lane 1 volume immediately upstream of the merge and compare this checkpoint volume. Adjustments were needed for truck volumes exceeding 5% or grades exceeding 3% as the equations represented mixed traffic on relatively level terrain.

5) Compare the checkpoint volume to the maximum service volume for the desired level of service, A through C.

The equations (or nomographs) related the volume on lane 1, V_1 to the total freeway volume immediately upstream of the subject ramp, V_F, the total volume on the subject ramp, V_R, the total volume on the adjacent upstream ramp, V_U, the total volume on the adjacent downstream ramp, V_D, the distance to the adjacent upstream ramp, D_U, and the distance to the adjacent downstream ramp, D_D. Each nomograph came with conditions for use and a step by step explanation on how to use it. The nomographs covered the following geometric configurations:

- Isolated on-ramp;
- Isolated off-ramp;
- Isolated on-ramp (loop);
- On-ramp with upstream/downstream off-ramp;
- Off-ramp with upstream on-ramp;
- Consecutive on-ramps; and
- On-ramp and off-ramp sequence.

There was one nomograph and two equations describing the geometric arrangement of a two-lane on-ramp connected to a 6 lane freeway with 3 lanes each direction. The following equations computed the volumes on lane 1 upstream of the ramp and within the merge area (HCM, 1965):

$$V_1 = 54 + 0.070V_f + 0.049V_r$$

$$V_{1+A} = -205 + 0.287V_1 + 0.5751V_r$$

where

V_1 = volume on the lane 1 of the freeway upstream of the merge

V_f = volume on the freeway main line

V_r = volume on the on-ramp

V_{1+A} = volume on lane 1 in the merge area

For the two-lane on-ramp, the application of the methodology was limited to freeway volumes between 600vph and 3000vph and ramp volumes of 1100vph to 3000vph, and required the acceleration lane to be at least 800ft.

The methodology of the 1985 HCM was largely the same as that of the 1965 HCM. A notable difference was that the methodology had been updated to use flow rates instead of service volumes. Additionally, the methodology had been extended to consider the design speed of the freeway, offering level of service criteria for freeways with 70 mph, 60 mph and 50 mph design speeds.

2.1.3 1994 and 1997 Updates. Significant changes to the HCM methodology to evaluate the operation of freeway ramps resulted from studies conducted under Project 3-37, "Capacity and Level of Service at Ramp-Freeway Junctions" of the National Cooperative Highway Research Program and were published in the 1994 update of the HCM. The Project 3-37 database was collected over 18 months throughout the US, consisting mainly of merge junctions on 6-lane freeway sections. The project resulted in a new set of equations with corresponding nomographs to calculate density in ramps.

The main change in these HCM updates was the identification of a "ramp influence area", which was identified as the stretch of the road most affected by the complex vehicle interactions that happen in merge and diverge segments. For an on-ramp (i.e.

merge), the influence area extended 1,500ft downstream of the physical merge point; for an off-ramp (i.e. diverge), the influence area extended 1,500ft upstream of the physical diverge point (Roess and Prassas, 2014).

The research also showed that the turbulence was most experienced in the right two lanes of the freeway, under stable traffic conditions. While the previous HCM methodology focused on predicting the volume on lane 1 immediately upstream of a ramp junction, this new procedure calculated the volume in both lanes 1 and 2 of the freeway.

In these HCM updates, the use of density as the measure of effectiveness became prevalent. Therefore, the calculated volume on lanes 1 and 2 was combined with the volume on the ramp to calculate density. Density was then associated to a level of service (LOS), A through F. For instance, densities less than or equal to 10 passenger cars per mile per lane were categorized as LOS A. A LOS F was given for those demand flows which exceeded the capacity of the merge/diverge area. Equations were provided to estimate the speeds on the inner freeway lanes and within the influence area, for uncongested operations.

The October 1994 update to the 1985 HCM described the methodology in three major steps and focused on an influence area of 1500ft including the acceleration lanes, and lanes 1 and 2 of the freeway. The first step was to predict the flow entering lanes 1 and 2 of the mainline using the freeway demand flow rate and a factor P_{FM}, which represents the proportion of vehicles expected to use lanes 1 and 2. Five equations were provided for determining the appropriate factor, P_{FM} for different junction configurations with single-lane on-ramps. These equations were calibrated to field data under Project 3-37. For two-lane on-ramps, the P_{FM} factor was given as 1.000, 0.555 and 0.2093 for four-lane, six-lane, and eight-lane freeway segments, respectively. The second step was to compare the demand to the critical capacity to determine whether traffic conditions are congested. The third step was to estimate the density as

$$D_R = 5.475 + 0.0734V_R + 0.0078V_{12} - 0.00627L_A$$

where

D_R = density in ramp influence area, pc/ln/mi

V_R = volume on the ramp, pc/hr

V_{12} = volume in lanes 1 and 2 on the freeway, pc/hr

L_A = length of the ramp acceleration lane, ft

For two lane ramps, the same density equation was used except that L_A was replaced by the effective length of the acceleration lanes, L_{Aeff} as computed by

$$L_{Aeff} = 2L_{A1} + L_{A2}$$

where

L_{A1} = length of the first acceleration lane

L_{A2} = length of the second acceleration lane

The methodology included in the 1994 Update was the basis for the methodologies of the 2000 and 2010 HCMs with a few relatively minor revisions (Roess and Prassas, 2014).

2.1.4 2000 and 2010 HCM. The methodology for analyzing freeway on-ramp junctions was detailed in Chapter 25 of the 2000 HCM. The methodology was described as having three major steps: 1) calculating the flow entering lanes 1 and 2 of the freeway immediately upstream of the influence area; 2) comparing the demand to the capacity of the merge segment to determine whether conditions are congested; and 3) estimating the density and speeds within the influence area.

In the 2010 HCM the methodology was described as a five step procedure: 1) calculating the flow rates; 2) calculating the flow rate in lanes 1 and 2 of the freeway immediately upstream of the merge influence area; 3) comparing the capacity of the merge area to the demand flow; 4) estimating the density; and 5) estimating the speeds.

Although rearranged, the procedure in the 2010 HCM was essentially the same as that of the 2000 HCM, with two notable changes. One notable change was the addition of another equation for calculating P_{FM}, the proportion of the freeway flow expected to remain in lanes 1 and 2, for an 8-lane freeway. The 2010 version also included a section discussing the reasonableness of the P_{FM} values.

Specific to the special case of a two-lane on-ramp, the P_{FM} values, and use of an effective length of the acceleration lane remained unchanged.

2.1.5 2016 HCM Methodology. The most recent edition of the HCM is the sixth edition published in 2016. The procedure for evaluating freeway on-ramps is provided in Chapter 14, with the procedure for two-lane on-ramps offered under a Special Cases section. The methodology is described as a five-step procedure, same as that in the 2010 HCM.

The first step of the methodology is to determine the flow rates on the freeway mainline and on-ramp. The second step is to estimate the freeway flow that is expected to remain in lanes 1 and 2 by multiplying the freeway volume, V_f by a factor P_{FM}. For analyzing two-lane on-ramps, P_{FM} = 1.00 for four-lane freeways, P_{FM} = 0.555 for six-lane freeways, and P_{FM} = 0.209 for eight-lane freeways. The calculated demand flows are then compared to the capacity of the freeway segment to determine whether or not the freeway segment is operating under uncongested or congested conditions. This check is done because the methodology is applicable to uncongested traffic conditions. The fourth step is to estimate the density in the ramp influence area.

$$D_R = 5.475 + 0.00734V_R + 0.0078V_{12} - 0.00627L_{Aeff}$$

where

D_R = density in ramp influence area, pc/ln/mi

V_R = flow rate (pc/hr) on the on-ramp

V_{12} = flow rate (pc/hr) on freeway lanes 1 and 2

L_{Aeff} = effective length of both acceleration lanes

The density is then translated into a level of service (LOS) as shown in Table I.

Table I. HCM Level of Service (LOS) Definitions

LOS	Density (pc/mi/ln)	Comments
A	≤ 10	Unrestricted operations
B	> 10 – 20	Merging and diverging maneuvers noticeable to drivers
C	> 20 – 28	Influence area speeds begin to decline
D	> 28 - 35	Influence area turbulence becomes intrusive
E	> 35	Turbulence felt by virtually all drivers
F		Ramp and freeway queues form

2.2 Research on Freeway On-Ramps

The changes to the HCM methodology since 1950 were based on a couple key pieces of research; the work by Joseph Hess and NCHRP Project 3-37. To gain a better understanding of what is already known about the operation of freeway on-ramps, a literature review was conducted. The results are summarized below.

Entrance ramps have caught the attention of many traffic flow researchers because they are major source of recurring traffic bottlenecks and lead to breakdown thus hindering mobility. Elefteriadou (1995) studied congestion that occurs in the vicinity of on-ramps and determined that breakdown is probabilistic unlike the HCM deterministic capacity breakdown definition. Roess (1984) found that traffic operations in the vicinity of on-ramp junctions can be significantly improved when upstream vehicles are guided to shift from the outside lanes to the inner lanes before arriving at on-ramp junctions. Al-Kaisy (1999) used INTEGRATION 2.0 to estimate the capacity of weave, merge and diverge sections and found that the most important factor in the merge area is the capacity of the freeway junction and the capacity of the ramp. The on-ramp capacities corresponding to the free flow speed on the on-ramp for both one-lane and two-lane on-ramps are shown in Table II.

Table II. On-Ramp Capacity for Ramp Free Flow Speed

Free Flow Speed of On-Ramp (miles/hour)	Capacity (passenger cars/hour)	
	One-Lane Ramp	Two-Lane Ramp
> 50	2200	4400
> 40 - 50	2100	4100
> 30 - 40	2000	3800
≥ 20 - 30	1900	3500
< 20	1800	3200

Merging is the action where two separate traffic streams form one, such as the flow from an on-ramp and the flow on the freeway mainline. To merge, a driver needs to perform several different tasks such as changing lanes to get into the desired lane, accelerating, decelerating, and finding adequate and available gaps to make these movements (Gettman 1998). According to Shin et al (1993), the capacity of an entrance ramp is a function of the ability of the merge section to accommodate the demand from the ramp and that of the mainline traffic. Many factors influence this such as the number of lanes, lane width and lateral clearance, and the availability of gaps on the adjacent expressway.

CHAPTER III

MODEL DEVELOPMENT

To investigate the effect of varying the lengths of the acceleration lanes of a two-lane on ramp on the operations of the ramp influence area, an experiment was conducted. Two different approaches were used to carry out this experiment. The first approach examined whether the deterministic analytic procedures of the Highway Capacity Manual and associated Highway Capacity Software would predict a change in the density of the influence area under changes to the acceleration lane lengths. The second approach examined whether a stochastic, microscopic traffic simulation model would predict a change in the operation of the influence area when the lengths of the acceleration lanes changed. In this Chapter, the experimental design and the models used in each of these approaches are described.

3.1 Experimental Design

The experiment was designed as a two-factor factorial. The length of the acceleration lanes was an independent variable. Recognizing that the volumes on the mainline and on-ramp impacts the operations of the ramp influence area, the volume was also included as an independent variable. The dependent variable was the traffic density within the influence area.

Five different on-ramp configurations were defined by varying the lengths of the first and second acceleration lanes, L_{A1} and L_{A2} respectively. The effective length of the acceleration lanes was kept constant (1500ft) to stay consistent with the HCM methodology. According to the Highway Capacity Manual (2016), merging causes the most turbulence in the area 1500ft downstream of the ramp in stable traffic conditions which applies to the scenarios defined in this research. The length of the first acceleration lane was varied between 100ft and 500ft, while the length of the second acceleration lane was varied from 1300ft to 500ft, as shown on Table IV. A graphical representation (not to scale) of the five scenarios follows in Figure 2 through Figure 6.

Two different volume sets were defined. The volumes were chosen to achieve uncongested conditions and be able to capture enough interaction between vehicles. The first volume set included a freeway volume, V_F=5000vph and an on-ramp volume, V_R=1000vph. The second set included a freeway volume, V_F=3500vph and an on-ramp volume, V_R=500vph. These volume sets were not expected to exceed the capacity of the merge area and therefore would not result in oversaturated (i.e. congested) conditions.

Table III. On Ramp Configurations for Five Scenarios

Scenario	First acceleration lane length, L_{A1} ft	Second acceleration lane length, L_{A2} ft
1	100	1300
2	200	1100
3	300	900
4	400	700
5	500	500

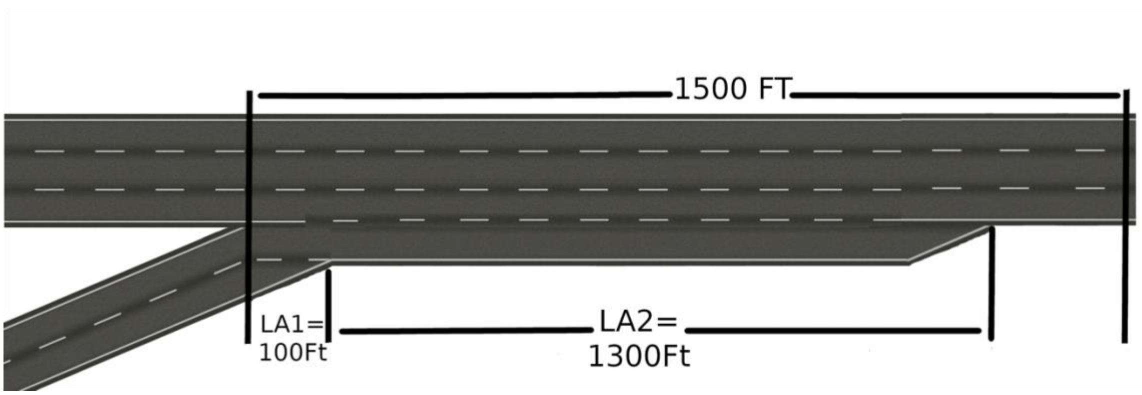

Figure 2. Graphical Representation of Scenario 1

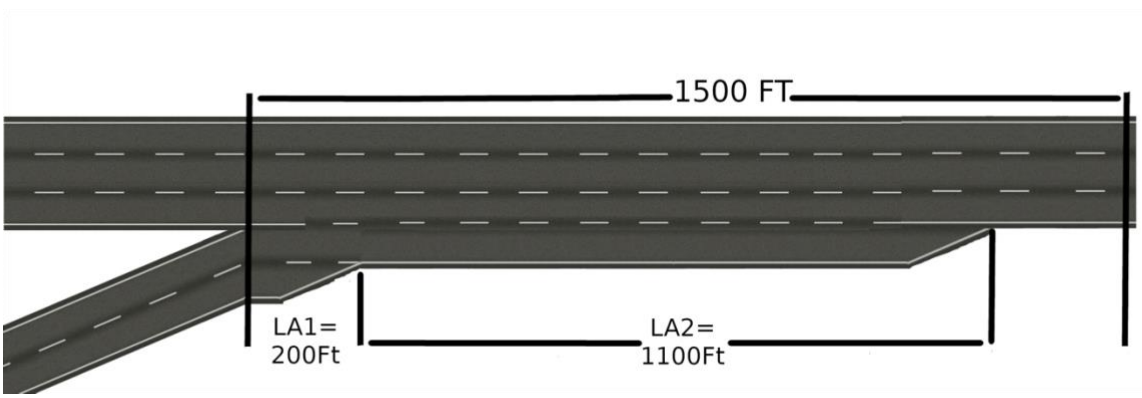

Figure 3. Graphical Representation of Scenario 2

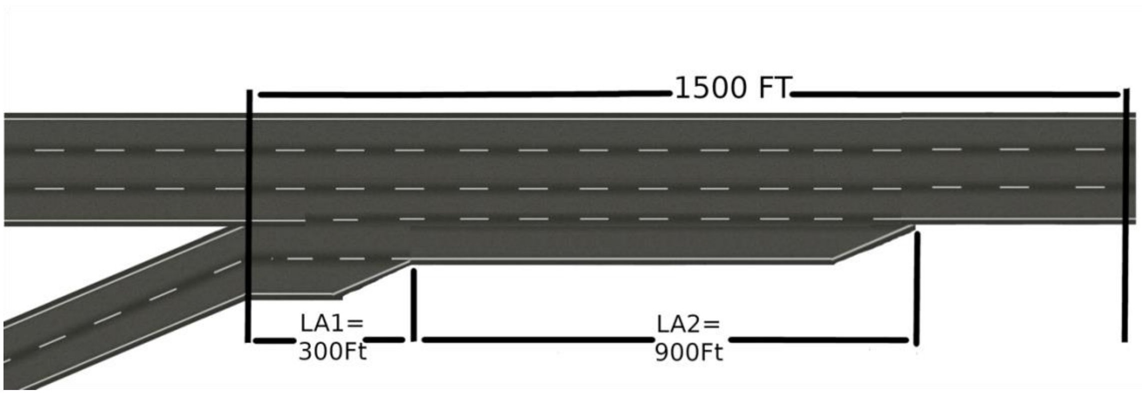

Figure 4. Graphical Representation of Scenario 3

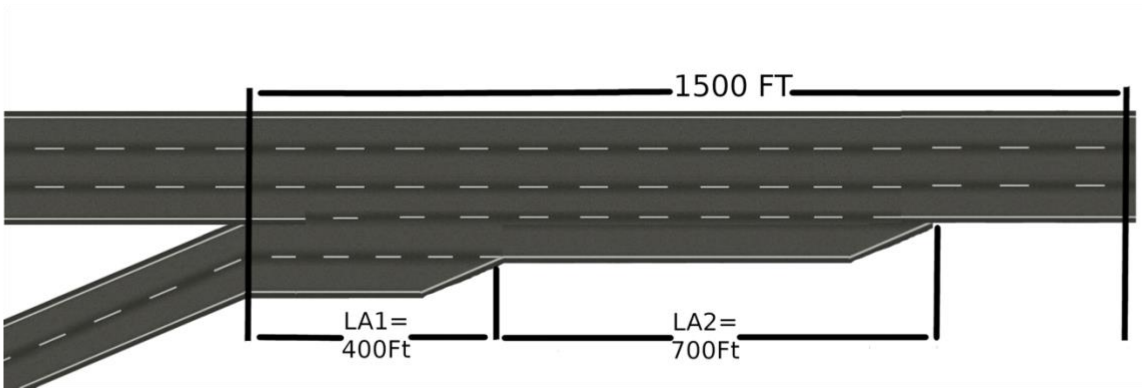

Figure 5. Graphical Representation of Scenario 4

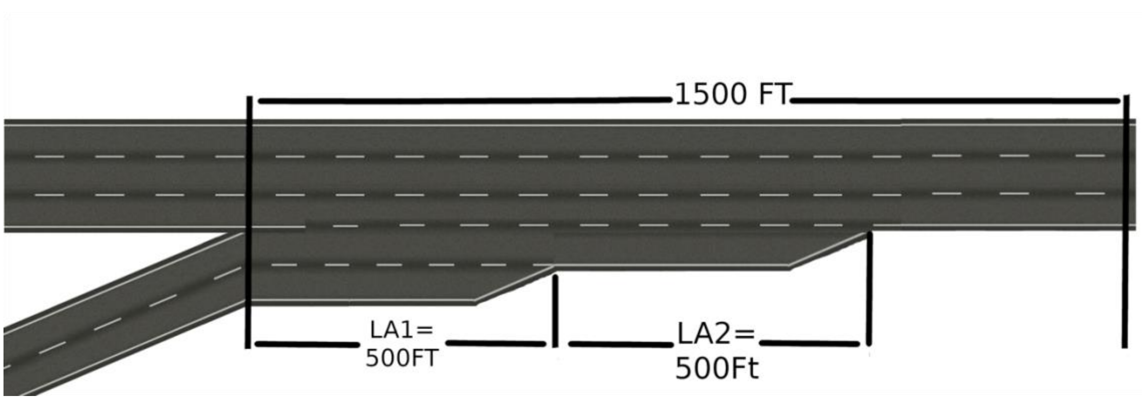

Figure 6. Graphical Representation of Scenario 5

3.2 Highway Capacity Software

HCS is a deterministic, macroscopic traffic analysis tool that implements the methodologies published in the HCM. It was originally developed as a companion to the 1985 HCM by the Center for Microcomputers in Transportation (McTrans) at the University of Florida that was founded by the Federal Highway Administration in 1986. The HCS was updated for the 2000 HCM, 2010 HCM and 2016 HCM.

3.2.1 HCS Model Setup. To setup the base model for the freeway on-ramp junction in the HCS, the following freeway ramp components were defined:

- 3 freeway lanes
- 70mph freeway free flow speed
- 2 ramp lanes
- 55mph ramp free flow speed
- Right side ramp connection
- No adjacent ramps

3.2.2 Ramp Influence Area Density Calculation. The HCS calculates the ramp influence area density according to the HCM methodology. The volume in the two outer lanes, V_{12} is estimated by

$$V_{12} = V_F \times P_{FM}$$

where

V_F=the volume on the freeway, pc/h

P_{FM}=the portion of the freeway mainline volume

- P_{FM}=1.000 for four-lane freeways
- P_{FM}=0.555 for six-lane freeways

- P_{FM}=0.209 for 8-lane freeways

The factor, P_{FM} represents the change in behavior observed on the freeway mainline. Under low flows, drivers will move to the inner lanes to avoid interacting with the on-ramp traffic flow. However, this factor does not take into account the change in this behavior that occurs between low-flow and high-flow traffic conditions. As traffic volumes increase, drivers are less likely to move to the inner lanes.

Once the volume in the two outside freeway lanes is estimated, the density of the influence area is calculated as

$$D_R = 5.475 + 0.00734V_R + 0.0078V_{12} - 0.00627L_{Aeff}$$

where

D_R=density, pc/ln/mi

V_R=flow rate (pc/hr) on the on-ramp

V_{12}=flow rate (pc/hr) on freeway lanes 1 and 2

L_{Aeff}=effective acceleration lane length, ft

The effective acceleration lane length is calculated using the lengths of the first and second acceleration lanes as

$$L_{Aeff} = 2L_{A1} + L_{A2}$$

where

L_{A1}=length of the first acceleration lane, ft

L_{A2}=length of the second acceleration lane, ft

The resulting density describes the amount of turbulence in the on-ramp influence area. This density is then translated to a level of service (LOS), as per Table I.

3.3 VISSIM

VISSIM is a microscopic traffic simulation software, developed by Planung Transport Verkehr (PTV) in Germany and distributed in the USA by PTV North America. Transportation networks are defined through links representing basic roadway segments and connectors, which join links together, and each is defined by a variety of attributes (e.g. number of lanes, lane width, speed). The vehicle flows are composed of a defined mix of vehicle types, drawn from different vehicle classes. The behavior of the vehicles is prescribed by the Wiedemann psycho-physical car-following model and the Sparmann lane changing model.

Lane changing behavior is divided into two types: 1) moving to a faster lane; and 2) moving to a slower lane. To make the lane change decision, three situations are evaluated: 1) whether there is a desire to change the lane; 2) whether the present driving situation in the neighboring lane is favorable; and 3) whether the movement to a neighboring lane is possible (Kan and Bhan, 2007). In VISSIM there are two kinds of lane changes: 1) necessary lane changes; and 2) free lane changes. The necessary lane change is applied when the vehicle needs to reach a connector. The free lane change happens when the vehicle is seeking more space or higher speed. No matter which type of lane change it is, the first step for the vehicles in VISSIM is to find a suitable gap (PTV, 2008).

The capabilities of the VISSIM software far exceeds the needs of this research. For this particular research question, VISSIM was used to create five simple network models of a freeway two-lane on-ramp junction with varying lengths of the first and second acceleration lanes and simulate their operation under a defined traffic volume.

3.3.1 VISSIM Model Setup: The freeway on-ramp junctions were modeled as a series of two merges, with each merge modelled by a single link representing all of the acceleration lanes and freeway mainline lanes. This approach was based on a recommendation from the Maryland Department of Transportation (MDOT, 2016).

Figure 7 illustrates how links and connectors were arranged to model the two-lane on-ramp merging with the three-lane freeway. Link 1 represented the three freeway lanes and Link 2 represented the two on-ramp lanes, upstream of the on-ramp merge. The first merge area was modelled by Link 3 with five lanes representing the three lanes on the freeway plus the two lanes of the on-ramp for the length of L_{A1}. The second merge area was modelled by Link 4 with four lanes representing three lanes of the freeway and the second acceleration lane for the length of L_{A2}. Link 5 represented the three lanes of the mainline freeway, downstream of the on-ramp merge. Connectors were defined to join each link with the next link immediately downstream.

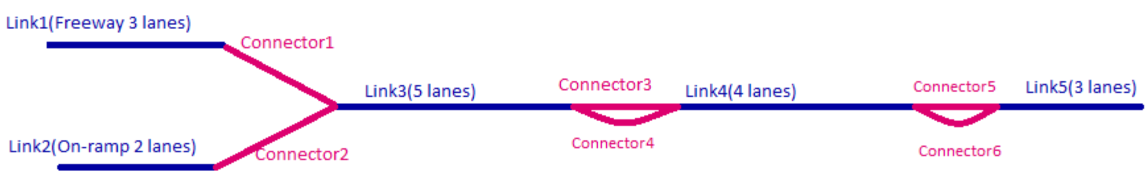

Figure 7. VISSIM Link and Connector Network

The five links were created by selecting Links from the Network Objects toolbar. Through the link dialog window, the number of lanes and width for each link was input. The configuration for the first freeway segment, Link 1 and the on-ramp, Link 2 are shown in Figure 8. The link length can only be modified manually through dragging the edge of the link. Many parameters can be changed to allow VISSIM users to model different scenarios and field conditions. In this model, the behavior type of each link was set to freeway (free lane selection).

To join links to each other, connectors were created. Connectors should be short, with only a small amount of overlap with the two links they connect. There are two important connector parameters that need to be adjusted by traffic modelers. The first one is the lane change distance, which is the distance before the downstream connector where vehicles begin to make lane changes. The second parameter is the emergency stop, which is the distance before the downstream connector where vehicles can make last chance lane changes. In this model, both these connectors parameters were left to their default values.

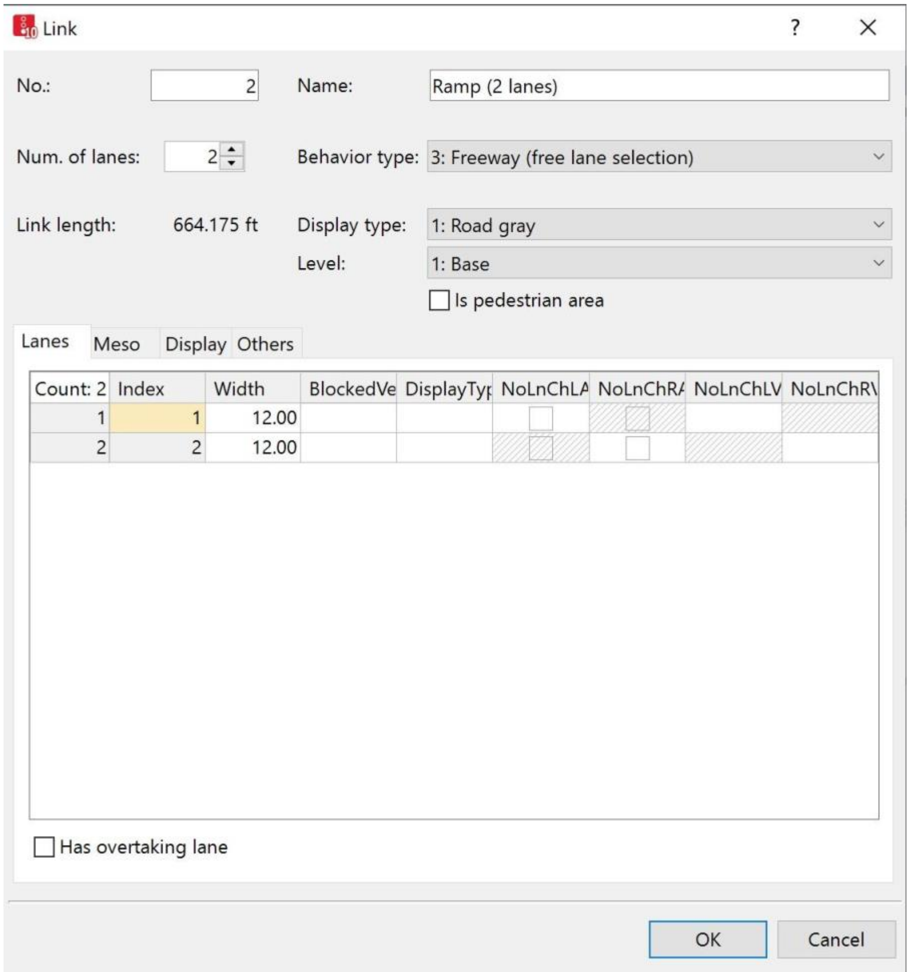

Figure 8. VISSIM Configuration for Link 2

3.3.2 Driver Behavior Parameters. The default VISSIM Wiedemann 99 driver behavior parameters (CCO, CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8, CC9) were used as shown in Table IV. The default parameters were recommended by different VISSIM protocols for State Department of Transportations around the nation, including VDOT, WSDOT, and ODOT as they adequately reflect the traffic conditions of a merge (MDOT, 2016).

Table IV. Wiedemann 99 Behavioral Parameters

Category	Code	Description	Value
Thresholds for Dx	CC0	Standstill distance: Desired distance between lead and following vehicle at v = 0 mph	4.92 ft
	CC1	Headway Time: Desired time in seconds between lead and following vehicle	0.9 sec
	CC2	Following Variation: Additional distance over safety distance that a vehicle requires	13.12 ft
	CC3	Threshold for Entering 'Following' State: Time in seconds before a vehicle starts to decelerate to reach safety distance	-8.00 sec
Thresholds for Dv	CC4	Negative 'Following' Threshold: Specifies variation in speed between lead and following vehicle	0.35 ft/s
	CC5	Positive 'Following Threshold': Specifies variation in speed between lead and following vehicle	0.35 ft/s
	CC6	Speed Dependency of Oscillation: Influence of distance on speed oscillation	11.44

Category	Code	Description	Value
Acceleration Rates	CC7	Oscillation Acceleration: Acceleration during the oscillation process	0.82 ft/s^2
	CC8	Standstill Acceleration: Desired acceleration starting from standstill	11.48 ft/s^2
	CC9	Acceleration at 50 mph: Desired acceleration at 50 mph	4.92 ft/s^2

3.3.3 Conflict Areas and Priority Rules. Conflict areas are regions where links and connectors overlap. Conflicting movements were resolved by setting the priority rules to code the merging of vehicles from the entrance ramp onto the freeway. Figure 9 depicts the conflict areas shown in green and red. VISSIM highlights the conflict areas after selecting the conflict area option from the Network Objects menu and allows users to define the right of way. In this model the vehicles on the entrance ramp were modeled to yield to the ones on the mainline. The status shows that vehicles travelling on the freeway have the right of way as shown in Figure 10 and Figure 11.

Figure 9. VISSIM Model Screenshot

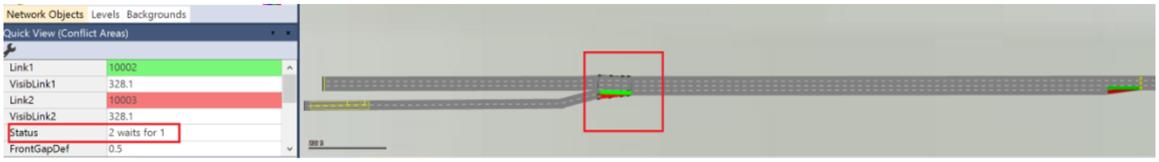

Figure 10. VISSIM First Conflict Area and Priority Rule

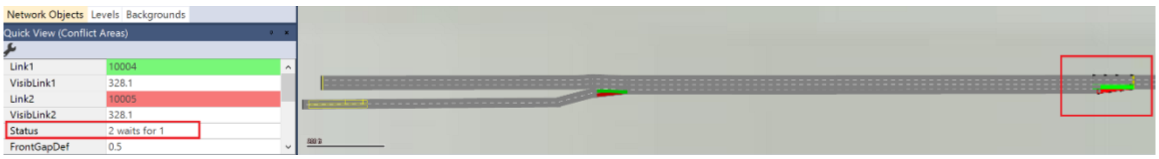

Figure 11. VISSIM Second Conflict Area and Priority Rule

3.3.4 Simulation Settings. The units of the model were set to imperial. To account for simulation variance, the simulation for each scenario was repeated five times using five random seed numbers 42, 40, 35, 38, and 39. According to the PTV Group website, random seeds change the start values of the random value generators used internally in the model which influences the arrival times of vehicle in the network, the driving behavior and also the selection of a certain distribution values wherever distributions are used. Those changes are comparable to the daily changes of the traffic patterns at the same location.

Each simulation was programmed to run for 1800 seconds. A warm-up period of approximately 120 seconds was included to allow time for the network to be populated before collecting traffic data. The simulation speed was set to maximum and the resolution to 10.Sim.sec. A high simulation resolution allows vehicles to make decisions at a higher frequency and get a smooth looking simulation.

3.3.5 Traffic Settings. Two sets of traffic volumes were chosen for the model simulation. The first set of volumes were 5000vph on the freeway with 1000vph on the ramp. The second set of volumes were 3500vph on the freeway and 500vph on the ramp.

The link volumes were assumed to be made up of only passenger cars and were consistent during the simulation.

The desired speed distributions for the freeway and ramp are shown on Figure 12 and Figure 13 respectively. For the mainline, the desired speed was set as a linear distribution from 69mph to 71mph as shown in the figure below. For the ramp, the desired speed was set as a linear distribution from 50mph to 65mph.

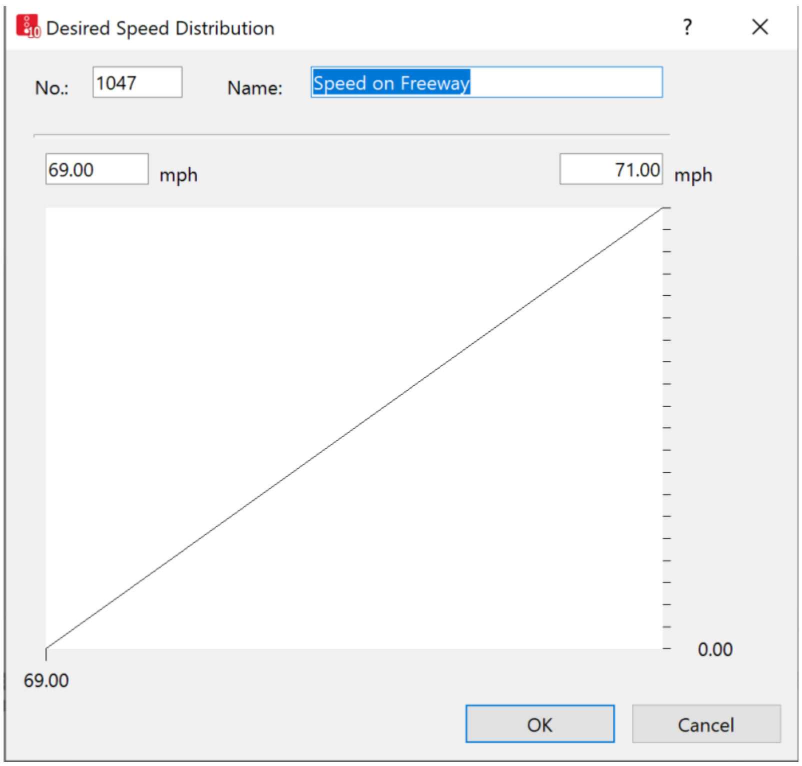

Figure 12. Desired Speed Distribution on the Freeway

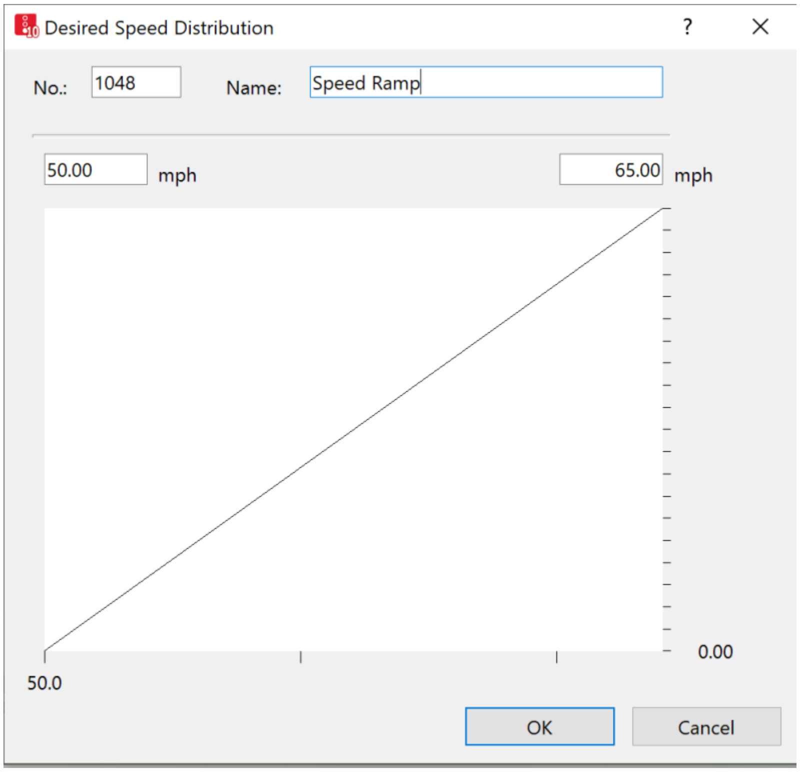

Figure 13. Desired Speed Distribution on the Ramp

Additional model parameters were defined. The grade of the road was set to terrain and all the parameters pertaining to vehicles such as their length, width, and acceleration rates were left to VISSIM default values. Along with all these parameters, a reduced speed area was added to the model. A reduced speed area is usually defined for turning movements in intersections. However, since lower speeds are usually observed in ramps, a reduced speed area was added to the ramp for a length of 150ft with a speed of 55mph. VISSIM allows users to define both acceleration and deceleration rates. In this model the deceleration rate and acceleration rate were left to their default value of $6.56 ft/s^2$

3.3.6 Data Collection. VISSIM can output various measures of effectiveness (MOEs) such as volume, speed, travel time, queue length, delay, density, etc. For the purpose of this experiment, two MOEs, density and delay were selected as reporting measures. From the main menu, the evaluation tab was selected to configure the model to collect this data. Data was collected for each link by lane. The start and end time for the link evaluation was set to the end of the warm-up period, and end of the simulation run, respectively.

3.3.7 Output. For each simulation run, the results were displayed in the Link Segment Results table as shown in Figure 14 and saved to an att file that could be imported to Excel.

Link Segment Results

Select layout...

Count: 6	SimRun	TimeInt	LinkEvalSegment	Density(All)	DelayRel(All)	Speed(All)	Volume(All)
5020	Average	120-180	3 - 2 - 0-5	6.98 /mi	1.31	66.37 mph	466.87 /h
5021	Average	120-180	3 - 3 - 0-5	17.59 /mi	0.12	69.79 mph	1227.65 /h
5022	Average	120-180	3 - 4 - 0-5	17.74 /mi	0.10	69.74 mph	1237.20 /h
5023	Average	120-180	3 - 5 - 0-5	17.65 /mi	0.08	69.83 mph	1232.03 /h
5024	Average	120-180	4 - 1 - 0-1030	10.42 /mi	6.67	62.97 mph	657.18 /h
5025	Average	120-180	4 - 1 - 1030-1211	15.31 /mi	46.92	35.61 mph	398.93 /h
5026	Average	120-180	4 - 2 - 0-1030	21.65 /mi	1.81	68.44 mph	1479.33 /h

Figure 14. VISSIM Link Segment Results

3.3.8 Ramp Influence Area Density Calculation. To be consistent with the HCS software performance measure, the density was calculated for the ramp influence area in VISSIM. Since there is no direct output from VISSIM for the ramp influence area density, the density for each of the four right lanes (the two acceleration lanes and two adjacent through lanes) were collected for Link3 for a distance equal to $L_{A1}$of the link and the densities for the three right lanes for Link4 were collected for a distance equal to L_{A2} . Recall that L_{A1} +L_{A2}= 1,500ft, which is the length of the influence area. The density of the ramp influence area was then estimated by calculating the average density across lanes (Milam et al, 2007).

CHAPTER IV

RESULTS AND ANALYSIS

The results of the HCM and VISSIM analyses are presented in this chapter. First the influence area density D_R with the corresponding LOS computed by HCS 2010 is presented, followed by the density in the ramp influence area resulting from the analysis of the VISSIM simulation runs.

4.1 HCS Results

The Highway Capacity Software was run for each combination of traffic volumes and acceleration lane lengths. A sample output is provided in Appendix A. Summaries of the results are provided in Appendix B. When the volume set was V_F=5000vph and V_R=1000vph, the analysis resulted in a density of 42.41pc/mi/ln, which is described by a LOS E. When the volume set was V_F=3500vph, V_R=500vph, the analysis resulted in a density of 27.04pc/mi/ln and a LOS C.

4.2 HCS Conclusions

Changing the lengths of the acceleration lanes L_{A1} and L_{A2} while keeping their effective length L_{Aeff} constant resulted in the same D_R and LOS for a given speed set. This is because the equation used in the HCS to compute D_R does not have L_{A1} and L_{A2}

as variables but instead includes the effective acceleration lane length, L_{Aeff}. Therefore, the current HCM methodology is insensitive to changes in acceleration lane length when the effective length remains constant. That result implies that the operation within the influence area does not benefit from changing how the effective length is delivered in terms of L_{A1} and L_{A2}.

4.3 VISSIM Results

Each VISSIM model was run five times using separate random seeds, for each combination of traffic volumes and acceleration lane lengths, for a total of 50 simulation runs. A sample VISSIM output is provided in Appendix C. Summaries of the lane and link density results output from VISSIM are provided in Appendix D. Using the lane and link density results, the density in the ramp influence area was calculated.

The density results, for each of the 50 simulation runs, are summarized in Table V through Table IX. The average density across the 5 random seeds, for each combination of traffic volumes and acceleration lengths, was calculated and included in the summary tables. The results for the first volume set are plotted on Figure 15 and the results from the second volume set are plotted on Figure 16.

Table V. Density in Ramp Influence Area for L_{A1}=100ft, L_{A2}=1300ft

Random Seed	Density (veh/ln/mi)	
	V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
35	16.48	17.46
38	21.3	16.89
39	17.38	13.78
40	20.58	18.1
42	18.02	14.81
Average	18.75	16.2

Table VI. Density in Ramp Influence Area for L_{A1}=200ft, L_{A2}=1100ft

Random Seed	Density (veh/ln/mi)	
	V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
35	24.97	12.01
38	22.04	16.24
39	28.67	18.06
40	26.09	12.71
42	20.20	20.08
Average	24.25	15.82

Table VII. Density in Ramp Influence Area for L_{A1}=300ft, L_{A2}=900ft

Random Seed	Density (veh/ln/mi)	
	V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
35	33.64	17.33
38	32.13	18
39	27.86	15.51
40	16.89	13.21
42	24.26	15.64
Average	26.96	15.94

Table VIII. Density in Ramp Influence Area for L_{A1}=400ft, L_{A2}=700ft

Random Seed	Density (veh/ln/mi)	
	V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
35	19.07	13.5
38	26.01	14.94
39	25.08	15.18
40	29.51	10.06
42	15	24.13
Average	22.93	15.56

Table IX. Density in Ramp Influence Area for L_{A1}=500ft, L_{A2}=500ft

Random Seed	Density (veh/ln/mi)	
	V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
35	31.66	11.32
38	28.26	13.79
39	27.68	17.35
40	26.75	12.17
42	25.85	21.19
Average	28.04	15.16

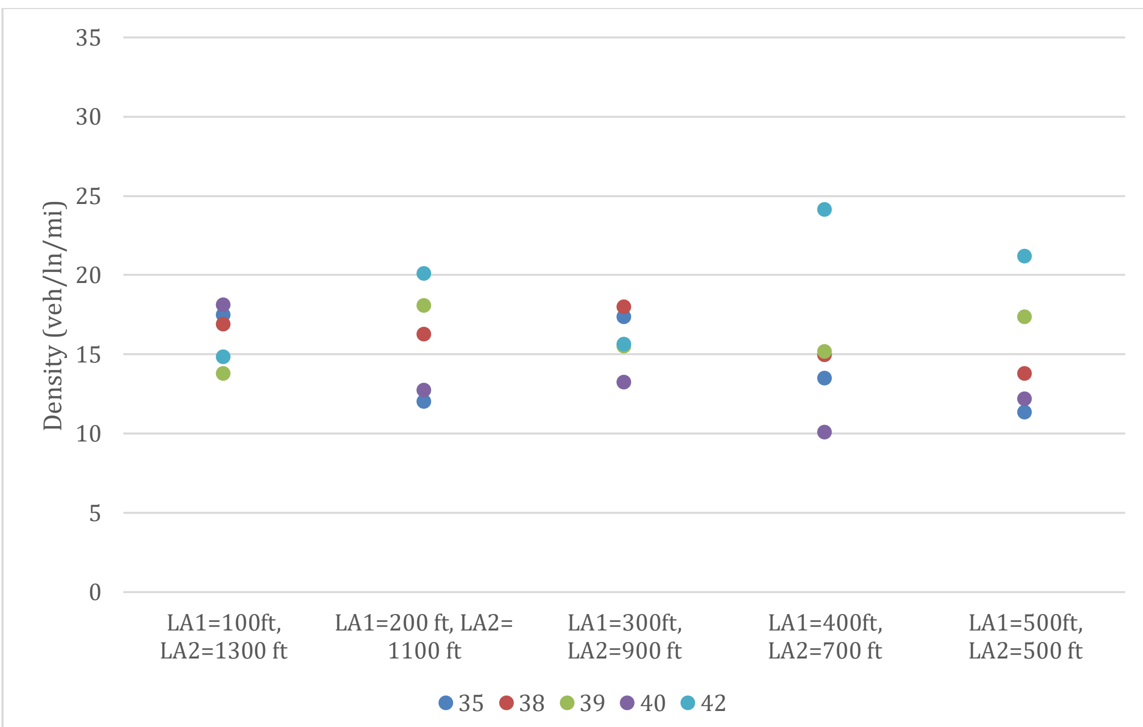

Figure 15. Ramp Influence Area Density V_F=5000vph, V_R=1000vph

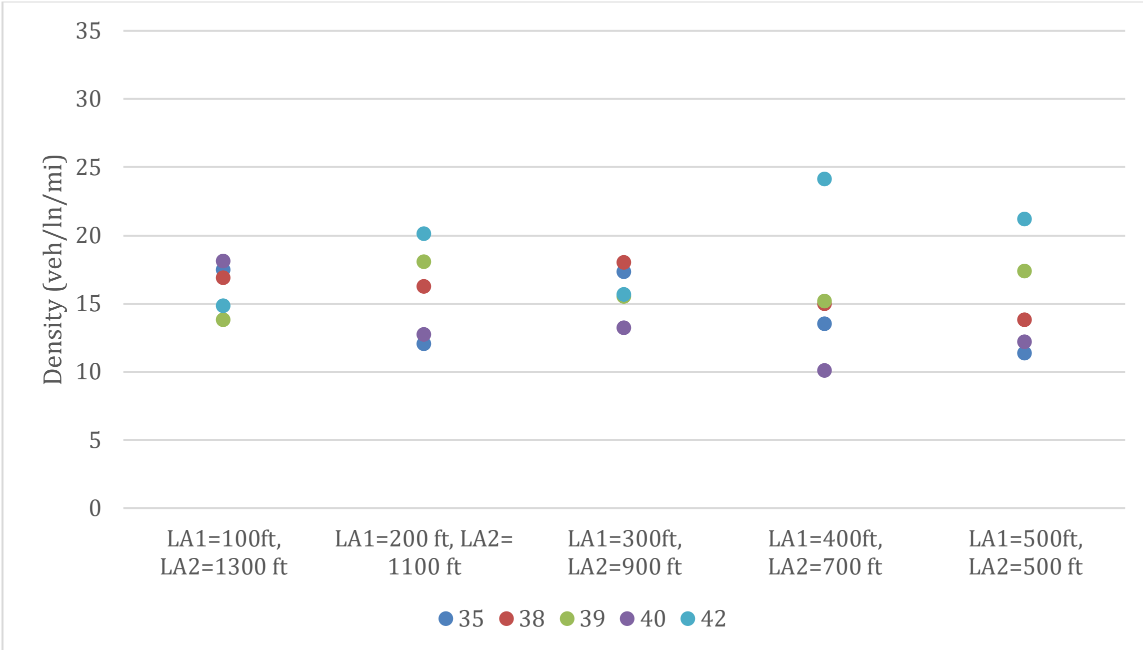

Figure 16. Ramp Influence Area Density V_F=3500vph, V_R=500vph

4.4 Analysis of VISSIM Results

To test whether the traffic volumes and lengths of the acceleration lanes effect the density in the ramp influence area, a two-way ANOVA analysis with repetition for the random seeds was conducted. The results are provided in Appendix E. The effect of changing the lengths of the acceleration lanes on the influence area density was not significant ($p=0.150$, $\alpha=0.05$) and the effect of changing the traffic volumes was significant ($p<0.001$, $\alpha=0.05$). The interaction between the effects was not significant ($p=0.066$, $\alpha=0.05$).

Given that the acceleration lane length and the density appeared to be positively related for the first volume set and negatively related for the second volume set, each dataset was analyzed separately using a one-way ANOVA. For the first volume set, V_F=5000vph, V_R=1000vph, the effect of the acceleration lane length was significant

(p=0.029, α=0.05). For the second volume set, V_F=3500vph, V_R=500vph, the effect of the acceleration lane length was not significant (p=0.992, α=0.05).

4.5 VISSIM Conclusions

As expected, the density in the influence area appeared to decrease when the traffic volumes were reduced from V_F=5000vph and V_R=1000vph to V_F=3500vph and V_R=500vph. This effect was found to be significant. The conclusion that can be drawn is that when there are larger conflicting flows vying for the same space, such as that which occurs within a merge section, vehicles become impeded and congestion occurs.

The density results under the various combinations of acceleration lane lengths appeared to increase as L_{A1} increased for volume set 1 (V_F=5000vph, V_R=1000vph) and decrease as L_{A1} increased for volume set 2 (V_F=3500vph, V_R=500vph). However, there was visible overlap in the density results across the acceleration lane lengths, for volume sets 1 and 2. Across both volume sets, the effect of the acceleration lane length on the influence area density was not found to be significant. However, when analyzed separately, the effect of the acceleration lane length on density was significant for the first volume set, V_F=5000vph, V_R=1000vph. The conclusion that can be drawn is that at the higher freeway and ramp volumes, an increase in L_{A1}+L_{A2} was associated with a decrease in influence area density.

4.6 Conclusions

The densities output by HCS and VISSIM were very different. For the first volume set, the HCS estimated a density of 42.41veh/ln/mi or LOS E and the VISSIM simulation results showed a range of average density from 18.75veh/ln/mi or LOS B to 28.04veh/ln/mi or LOS C. For the second volume set, the HCS estimated a density of

27.04veh/ln/mi or LOS C and the VISSIM simulation results showed a range of average density from 15.16veh/ln/mi or LOS B to 16.2veh/ln/mi or LOS C. The conclusion that can be drawn from these results is that the two modeling approaches were not comparable.

The HCM/HCS procedure is based on regression equations developed under NCHRP Project 3-37 and first introduced into the HCM for the October 1994 Update. The regression equations were developed based on field data and estimate density in the influence, D_R as a function of the ramp volume, V_R, the volume on the outer two freeway lanes, V_{12}, and the length of the acceleration lane, L_A, as

$$D_R = 5.475 + 0.0734V_R + 0.0078V_{12} - 0.00627L_A$$

For two lane ramps, the same density equation is used except that L_A is replaced by the effective length of the acceleration lanes, L_{Aeff}, as

$$L_{Aeff} = 2L_{A1} + L_{A2}$$

The VISSIM model describes the movement and interaction of individual vehicles. For this experiment, the default car-following and lane-changing parameters were retained. The conclusion that can be drawn is that the default driver behavior in VISSIM, and the chosen speed profiles were not representative of the field operations that were observed to develop the regression equations for the HCM procedure.

CHAPTER V

DISCUSSION AND FUTURE WORK

The experiment was designed to investigate the impact of the acceleration lane lengths and traffic volumes on the density of the on-ramp influence area for an isolated, two-lane on-ramp. The HCM equation for estimating the influence area density includes both of these variables and therefore an effect was expected. The one-way ANOVA results indicated that the acceleration lane length impacted the density under the higher volume set but not under the lower volume set. While the two-way ANOVA results indicated that the volume impacted the density. These relationships are further discussed as they pertain to the HCM influence area density equation, along with some thoughts about future work.

5.1 Current HCM Influence Area Density Equation

To begin this discussion, the current HCM equation for calculating the influence area density and its recommended use were reviewed. Recall the basic equation is

$$D_R = 5.475 + 0.0734V_R + 0.0078V_{12} - 0.00627L_A$$

where

D_R=density in the ramp influence area, pc/ln/mi

V_R=the ramp volume, pc/h

V_{12}=the volume on lanes 1 and 2 of the freeway, pc/h

L_A=the length of the acceleration lane, ft

For the application of this equation, the influence area is assumed to be 1500ft and as such, it is not recommended to use an acceleration lane length greater than 1500ft, thus extrapolating beyond what the equation was calibrated for. When field data is not available, the recommended input is 800ft. However, there is no guidance as to a minimum value for the acceleration lane length.

What is concerning about this equation is the constant term. When the flows on the ramp and freeway lanes 1 and 2 are zero, the density in the influence area is estimated to be 5.475 pc/mi/ln, which does not make sense. By the fundamental traffic flow theory, density is either zero or at jam density when the flow is zero. Jam density occurs when traffic has come to a stop (LOS F), and vehicles are spaced at their minimum headway.

In the previous HCM methodology, the equations and nomographs for estimating the volumes in the outer freeway lane (i.e. lane 1) included a restriction that the length of the acceleration lane needed to be at least 800ft. If that restriction applies to the current equation, then the $-0.00627L_A$ term becomes an adjustment for acceleration lanes greater than 800 ft.

Perhaps it could be argued that L_A needs to be removed from the influence area density equation and applied as an adjustment to the calculated density when the acceleration lane length exceeds some reference value to account for the additional space vehicles have to merge onto the freeway. The constant term could be forced to zero by setting the reference acceleration lane length to 885ft. Then each additional 160ft of acceleration lane length would be addressed by applying a density reduction of 1pc/ln/mi.

This is approximately the marginal impact of the acceleration lane length in the current HCM equation.

Given the effect of the lengths of the acceleration lanes was not significant at the low volume set but was significant at the higher volume set, it could be argued that the adjustment to the density could depend on the traffic volumes. At low volumes, an adjustment there may be warranted, as vehicles have ample opportunity to merge into the outer freeway lane. At high volumes, with fewer usable gaps in the freeway traffic, the longer acceleration lanes increase the opportunity to merge. Thus, the adjustment for the length of the acceleration lanes may be greater under higher traffic volumes.

5.2 Current HCM Influence Area Density Equation for Two-Lane On-Ramps

For the special case of a two-lane on-ramp, the length of the acceleration lane, L_A in the influence area density equation is replaced with the effective length of acceleration lane, L_{Aeff}. The effective length of acceleration lane is equal the total length of the acceleration lanes, $2L_{A1} + L_{A2}$.

Operationally, the two lengths, L_A and L_{Aeff} are not equivalent. The vehicles on L_A have direct access to the gaps in the outer lane of the freeway. The vehicles on the inner lane of the two-lane on-ramp, which has a length $L_{A1}+L_{A2}$ also have direct access, however the vehicles on the outer lane do not. Those vehicles must first merge onto the inner acceleration lane. Perhaps a better replacement for L_A would be $L_{A1}+L_{A2}$, since each has direct access to lane 1 of the freeway.

5.3 Contributions of Thesis

This research was done to examine whether changing the lengths of the acceleration lanes effects the operation of the ramp influence area and was motivated by the notion that two-lane on-ramps will produce less turbulence on the mainline than a comparable one-lane on-ramp. If the design of two-lane ramps can be manipulated to control the density impact, then there may be potential to design on-ramps to satisfy some congestion criterion.

Based on the HCM equation for estimating the influence ramp density, an increase in the acceleration lane length L_A is expected to reduce the density in the influence area. For two-lane on-ramps, the L_A term is replaced by $L_{Aeff}=2L_{A1}+L_{A2}$. When using a constant L_{Aeff} changes to L_{A1} and L_{A2} are not expected to impact the density. This was illustrated through the HCM/HCS analysis. However, the VISSIM results indicated that changing L_{A1} and L_{A2} did impact the density. When $L_{A1}+L_{A2}$ was used to represent the length of the acceleration lane, the results for the first volume set indicate that the density decreases as $L_{A1}+L_{A2}$ increases. This result led to the thinking that it is not appropriate to replace L_A with L_{Aeff}.

The freeway and ramp flows were also included in the investigation and were expected to have a positive linear relationship with the density. The results of the experiment indicated such a relationship, and the effect of the traffic volumes was found to be significant. In this respect, the results were consistent with the HCM equation.

The experiment, and associated results, represent the beginning of a line of inquiry that has the potential to impact the way in which two-lane on-ramps are designed and analyzed. It is just a beginning. While addressing one question, many others have surfaced. Those questions are discussed next.

5.4 Expanding Upon Thesis

In this experiment, a constant L_{Aeff} was used and assigned to L_{A1} and L_{A2} in five different ratios 100ft:1300ft, 200ft:1100ft, 300ft:900ft, 400ft:700ft, and 500ft:500ft. If these acceleration lengths are described in terms of $L_{A1}+L_{A2}$, it represents a range from 1000ft to 1400ft. If L_{Aeff} was allowed to vary, a value of $L_{A1}+L_{A2}$ could be achieved through various combinations of lane lengths. For instance, $L_{A1}+L_{A2}$=1000ft could be achieved using L_{A1}=500ft, L_{A2}=500ft with L_{Aeff}f=1500ft, or L_{A1}=300ft, L_{A2}=700ft with L_{Aeff}=1300ft. The question that is then posed is; Does the density change when $L_{A1}+L_{A2}$ is held constant but L_{Aeff} is allowed to vary? The results of such an investigation would shed light on the operational difference of including the outer acceleration lane. If the inclusion of the outer acceleration lane does not improve the density in the influence area, then it only serves as a queueing area for vehicles wanting to merge onto the freeway.

If $L_{A1}+L_{A2}$ replaces L_A in the HCM equation, a range in acceleration lane length of 1000ft to 1400ft would yield and expected change in density of approximately 2.5pc/mi/ln. Comparing the average densities, a difference of 9.288 was recorded for the first volume set, V_F=5000vph, V_R=1000vph, and a difference of -1.044 was recorded for the second volume set, V_F=3500vph, V_R=500vph. This raises the question of whether the impact of the acceleration lane length becomes more prevalent as the volumes increase. In the VISSIM model, of the volume sets generated densities in the influence area represented by LOS B and C. The experiment should be expanded to examine the effect of the acceleration lane lengths under higher freeway and ramp volumes, creating conditions representing LOS C, D and E.

Expanding upon this thesis by investigating whether changing L_{Aeff}, while holding $L_{A1}+L_{A2}$ constant impacts the influence area density, and whether the impact of the acceleration lane length, $L_{A1}+L_{A2}$ on the influence area density increases at higher freeway and ramp volumes, will provide a better understanding of the potential operational benefits of isolated two-lane on-ramps. That understanding could lead to changes in the design and use of two-lane on ramps to improve freeway traffic flow.

5.5 Expanding Beyond the Thesis

The experiment was designed for an isolated two-lane on-ramp operating with fixed freeway and ramp speeds. These conditions represent a very specific application for a two-lane on-ramp. In reality, operating conditions can include the presence of upstream ramps which can influence the operation of the ramp junction, a range of freeway and ramp volumes, and a range of freeway and ramp speeds. These are factors considered in the HCM methodology and could be explored for two-lane on-ramps.

When designing the experiment, the L_{Aeff} was set to 1500ft to coincide with the recognized length of the influence area. This length was established through NCHRP Project 3-37, which dates back to over 50 years ago. Changes in driving population, vehicle performance and safety features, may have impacted merge behavior and thus the length of the influence area. This is a topic that could be revisited. For instance, it would be interesting to see whether the length of the acceleration lane itself, or the inclusion of the outer lane of a two-lane on-ramp, are contributing factors to the extent of the disruption to the freeway traffic lanes, as represented by the influence area.

The overall purpose of learning what conditions impact the operation of two-lane on-ramps and to what extent two-lane on-ramps impact the operations of the freeway, is to be able to better design freeway ramp junctions to meet the needs of its users. Improving upon the operation of freeway junctions has the potential to improve traffic flow. The effectiveness of the junction improves as more vehicles are serviced, and the efficiency of the junction improves as the occurrence and severity of congestion is reduced, the benefits of which include improved mobility and reduced environmental impact.

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Appendix A. Sample HCS Output

```
     v                      6383          7200            No
      FO
     v  or v                1893 pc/h     (Equation 13-14 or 13-17)
      3     av34
Is   v  or v       > 2700 pc/h?           No
      3     av34
Is   v  or v       > 1.5 v  /2            Yes
      3     av34          12
If yes, v    = 2431                    (Equation 13-15, 13-16, 13-18, or 13-19)
         12A
________________________Flow Entering Merge Influence Area_____________________
                      Actual        Max Desirable         Violation?
     v                4559          4600                  No
      12A
_________________Level of Service Determination (if not F)_____________________

Density, D = 5.475 + 0.00734 v  + 0.0078 v   - 0.00627 L   =   30.7    pc/mi/ln
          R                   R          12            A
Level of service for ramp-freeway junction areas of influence  D

_____________________________Speed Estimation__________________________________

Intermediate speed variable,                 M  = 0.528
                                              S
Space mean speed in ramp influence area,     S  = 55.2    mph
                                              R
Space mean speed in outer lanes,             S  = 65.2    mph
                                              0
Space mean speed for all vehicles,           S  = 57.7    mph
_______________________________________________________________________________
```

Figure 17. Sample HCS Output

Appendix B. HCS Results

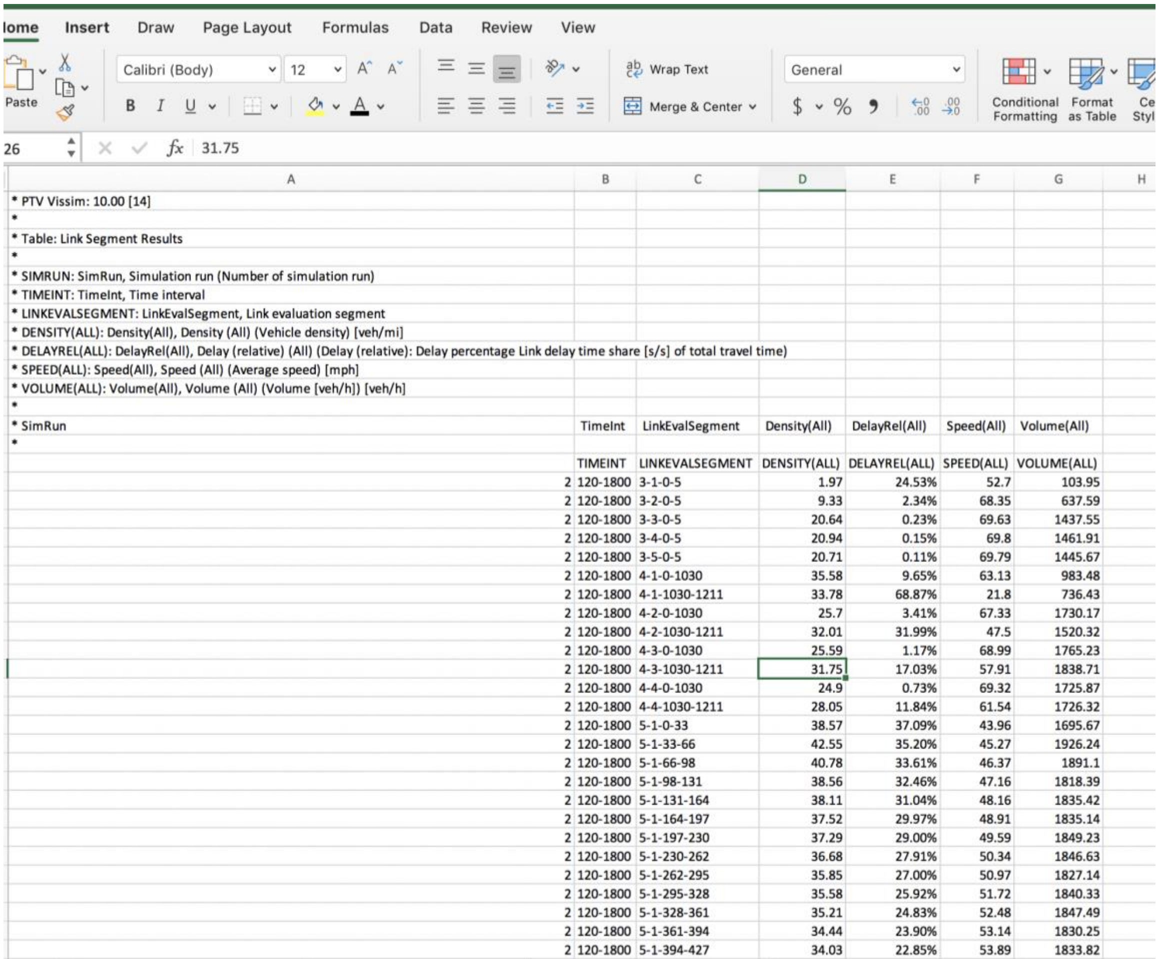
Table X. HCS 2010 Density and LOS Results for First Set of Volumes

Scenario	D_R (pc/mi-ln)	LOS
L_{A1} =100 ft, L_{A2}=1300 ft	42.41	E
L_{A1} =200 ft, L_{A2}=1100 ft	42.41	E
L_{A1} =300 ft, L_{A2}=900 ft	42.41	E
L_{A1} =400 ft, L_{A2}=700 ft	42.41	E
L_{A1} =500 ft, L_{A2}=500 ft	42.41	E

Table XI. HCS 2010 Density and LOS Results for Second Set of Volumes

Scenario	D_R (pc/mi-ln)	LOS
L_{A1} =100 ft, L_{A2}=1300 ft	27.04	C
L_{A1} =200 ft, L_{A2}=1100 ft	27.04	C
L_{A1} =300 ft, L_{A2}=900 ft	27.04	C
L_{A1} =400 ft, L_{A2}=700 ft	27.04	C
L_{A1} =500 ft, L_{A2}=500 ft	27.04	C

Appendix C. Sample VISSIM Output



* PTV Vissim: 10.00 [14]
*
* Table: Link Segment Results
*
* SIMRUN: SimRun, Simulation run (Number of simulation run)
* TIMEINT: TimeInt, Time interval
* LINKEVALSEGMENT: LinkEvalSegment, Link evaluation segment
* DENSITY(ALL): Density(All), Density (All) (Vehicle density) [veh/mi]
* DELAYREL(ALL): DelayRel(All), Delay (relative) (All) (Delay (relative): Delay percentage Link delay time share [s/s] of total travel time)
* SPEED(ALL): Speed(All), Speed (All) (Average speed) [mph]
* VOLUME(ALL): Volume(All), Volume (All) (Volume [veh/h]) [veh/h]
*

* SimRun	TimeInt	LinkEvalSegment	Density(All)	DelayRel(All)	Speed(All)	Volume(All)
*						
	TIMEINT	LINKEVALSEGMENT	DENSITY(ALL)	DELAYREL(ALL)	SPEED(ALL)	VOLUME(ALL)
2	120-1800	3-1-0-5	1.97	24.53%	52.7	103.95
2	120-1800	3-2-0-5	9.33	2.34%	68.35	637.59
2	120-1800	3-3-0-5	20.64	0.23%	69.63	1437.55
2	120-1800	3-4-0-5	20.94	0.15%	69.8	1461.91
2	120-1800	3-5-0-5	20.71	0.11%	69.79	1445.67
2	120-1800	4-1-0-1030	35.58	9.65%	63.13	983.48
2	120-1800	4-1-1030-1211	33.78	68.87%	21.8	736.43
2	120-1800	4-2-0-1030	25.7	3.41%	67.33	1730.17
2	120-1800	4-2-1030-1211	32.01	31.99%	47.5	1520.32
2	120-1800	4-3-0-1030	25.59	1.17%	68.99	1765.23
2	120-1800	4-3-1030-1211	31.75	17.03%	57.91	1838.71
2	120-1800	4-4-0-1030	24.9	0.73%	69.32	1725.87
2	120-1800	4-4-1030-1211	28.05	11.84%	61.54	1726.32
2	120-1800	5-1-0-33	38.57	37.09%	43.96	1695.67
2	120-1800	5-1-33-66	42.55	35.20%	45.27	1926.24
2	120-1800	5-1-66-98	40.78	33.61%	46.37	1891.1
2	120-1800	5-1-98-131	38.56	32.46%	47.16	1818.39
2	120-1800	5-1-131-164	38.11	31.04%	48.16	1835.42
2	120-1800	5-1-164-197	37.52	29.97%	48.91	1835.14
2	120-1800	5-1-197-230	37.29	29.00%	49.59	1849.23
2	120-1800	5-1-230-262	36.68	27.91%	50.34	1846.63
2	120-1800	5-1-262-295	35.85	27.00%	50.97	1827.14
2	120-1800	5-1-295-328	35.58	25.92%	51.72	1840.33
2	120-1800	5-1-328-361	35.21	24.83%	52.48	1847.49
2	120-1800	5-1-361-394	34.44	23.90%	53.14	1830.25
2	120-1800	5-1-394-427	34.03	22.85%	53.89	1833.82

Figure 18. Sample VISSIM Output

Appendix D. VISSIM Results

Table XII. D_R, L_{A1}=100ft, L_{A2}=1300ft, Random Seed=40

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	1.97	3.69
3	2	9.33	16.90
3	3	20.64	16.26
4	1	20.71	16.23
4	2	15.58	17.44
4	3	31.75	18.40
4	4	44	14.76
D_R		20.58	14.81

Table XIII. D_R, L_{A1}=100ft, L_{A2}=1300ft, Random Seed=35

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	1.49	4.46
3	2	5.08	2.81
3	3	13.85	15.69
4	1	33.86	13.65
4	2	14.03	15.24
4	3	30.6	16.94
4	4	35	19.56
D_R		16.48	11.46

Table XIV. D_R, L_{A1}=100ft, L_{A2}=1300ft, Random Seed=38

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	4.89	8.09
3	2	7.9	8.20
3	3	20.41	17.44
4	1	33.6	18.40
4	2	14.05	7.47
4	3	29.07	18
4	4	39.7	7.5
D_R		21.3	12.15

Table XV. D_R, L_{A1}=100ft, L_{A2}=1300ft, Random Seed=39

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	4.89	1.69
3	2	7.9	7.58
3	3	20.41	7.38
4	1	20.5	18
4	2	14.05	18.05
4	3	28.28	17.49
4	4	25.68	19.27
D_R		17.38	12.78

Table XVI. D_R, L_{A1}=100ft, L_{A2}=1300ft, Random Seed=42

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	4.38	1.2
3	2	13.85	5.47
3	3	33.77	15
4	1	23.81	17
4	2	19.14	17.44
4	3	16.22	18.4
4	4	15.03	17.25
D_R		18.02	13.1

Table XVII. D_R, L_{A1}=200ft, L_{A2}=1100ft, Random Seed=40

Link	Lane	Density 1(veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	5.42	3.5
3	2	10.24	9
3	3	23.56	14.98
4	1	34.69	14.46
4	2	24.91	9.67
4	3	46.91	23.1
4	4	36.94	14.45
D_R		26.09	12.71

Table XVIII. D_R, L_{A1}=200ft, L_{A2}=1100ft, Random Seed=35

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	5.07	6
3	2	11.56	11
3	3	23.56	16.91
4	1	27.13	14.42
4	2	24.12	15.31
4	3	45.03	21
4	4	38.34	17
D_R		24.97	14.01

Table XIX. D_R, L_{A1}=200ft, L_{A2}=1100ft, Random Seed=38

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	6.06	9.97
3	2	13.65	10.65
3	3	24.9	19.8
4	1	31.3	12.28
4	2	20.74	15.79
4	3	37.8	41
4	4	46.01	42
D_R		22.04	18.24

Table XX. D_R, L_{A1}=200ft, L_{A2}=1100ft, Random Seed=39

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	5.34	12.04
3	2	41.21	34
3	3	24.14	15.98
4	1	25.33	10.5
4	2	29	12.09
4	3	47.01	23
4	4	34	37.27
D_R		28.67	20.69

Table XXI. D_R, L_{A1}=200ft, L_{A2}=1100ft, Random Seed=42

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	6.38	17
3	2	11.5	13.6
3	3	21.22	42.3
4	1	30.85	21.07
4	2	18.92	10.54
4	3	34.7	32.1
4	4	17.87	11
D_R		20.20	21.08

Table XXII. D_R, L_{A1}=300ft, L_{A2}=900ft, Random Seed=40

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	10.01	2.3
3	2	15.83	8.26
3	3	27.35	18.82
4	1	38.81	22.26
4	2	28.71	19
4	3	37.51	22.26
4	4	30.77	13.87
D_R		26.99	15.25

Table XXIII. D_R, L_{A1}=300ft, L_{A2}=900ft, Random Seed=35

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	7.38	8.96
3	2	17.10	6.7
3	3	40.31	26.14
4	1	42.33	26.9
4	2	47.57	23.8
4	3	47.55	16.74
4	4	33.26	12.09
D_R		33.64	17.33

Table XXIV. D_R, L_{A1}=300ft, L_{A2}=900ft, Random Seed=38

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	6.41	2.59
3	2	13.75	1.47
3	3	26.75	16.93
4	1	56.50	47.18
4	2	48.97	23.84
4	3	40.75	17.21
4	4	31.8	16.82
D_R		32.13	18

Table XXV. D_R, L_{A1}=300ft, L_{A2}=900ft, Random Seed=39

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	8.10	3.35
3	2	25.81	1.43
3	3	25.59	13.62
4	1	32.69	42.5
4	2	49.39	15.85
4	3	25.63	16.35
4	4	21.92	16.39
D_R		27.86	15.51

Table XXVI. D_R, L_{A1}=300ft, L_{A2}=900ft, Random Seed=42

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	7.10	6.52
3	2	12.97	5.97
3	3	24.43	17.50
4	1	34.76	26.99
4	2	31.63	17.49
4	3	34.67	17.50
4	4	30.32	17.57
D_R		24.26	15.64

Table XXVII. D_R, L_{A1}=400ft, L_{A2}=700ft, Random Seed=35

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	7.03	3.4
3	2	3.56	7.06
3	3	20.06	9.93
4	1	19.8	14.19
4	2	25.9	16.09
4	3	15.31	19.04
4	4	16	14.87
D_R		19.07	15.18

Table XXVIII. D_R, L_{A1}=400ft, L_{A2}=700ft, Random Seed=38

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	12.34	1.84
3	2	5.70	1,21
3	3	15	13.88
4	1	28.9	21.67
4	2	18.1	12.65
4	3	21.65	22.06
4	4	27.22	17.54
D_R		26.01	14.94

Table XXIX. D_R, L_{A1}=400ft, L_{A2}=700ft, Random Seed=39

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	8.99	2.15
3	2	7.52	3.12
3	3	19.8	11.32
4	1	27.74	6.84
4	2	14.29	11.19
4	3	28.68	19.11
4	4	24	15.48
D_R		25.08	10.06

Table XXX. D_R, L_{A1}=400ft, L_{A2}=700ft, Random Seed=40

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	7.24	5.63
3	2	9.98	0.41
3	3	11.06	5.09
4	1	17.57	10.6
4	2	19.17	18.31
4	3	12.31	16.25
4	4	14.8	22.43
D_R		15	13.5

Table XXXI. D_R, L_{A1}=400ft, L_{A2}=700ft, Random Seed=42

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	13.94	0.6
3	2	8.70	5.8
3	3	27.11	17.35
4	1	19.56	9.87
4	2	29.04	22
4	3	14.06	18.13
4	4	33.94	17.70
D_R		29.51	24.13

Table XXXII. D_R, L_{A1}=500ft, L_{A2}=500ft, Random Seed=35

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	13.41	2.54
3	2	14.06	4.42
3	3	20.42	16
4	1	50.05	23
4	2	46	21.03
4	3	43.73	24.36
4	4	34	12.93
D_R		31.66	11.32

Table XXXIII. D_R, L_{A1}=500ft, L_{A2}=500ft, Random Seed=38

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	9.35	1.42
3	2	18.84	5.87
3	3	38.06	17.74
4	1	36.72	18.61
4	2	28.9	23.39
4	3	32	29.04
4	4	34	18.12
D_R		28.26	18.79

Table XXXIV. D_R, L_{A1}=500ft, L_{A2}=500ft, Random Seed=39

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	2.30	2.59
3	2	16.12	12.73
3	3	36.54	12.73
4	1	42.44	21.05
4	2	22	19.91
4	3	16.99	25.43
4	4	32	14.56
D_R		27.68	17.35

Table XXXV. D_R, L_{A1}=500ft, L_{A2}=500ft, Random Seed=40

Link	Lane	Density (veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	3.9	4.78
3	2	8.89	16.76
3	3	25.88	13.84
4	1	50.12	20
4	2	36.91	19.28
4	3	24.7	17.06
4	4	36.91	16.09
D_R		26.75	17.17

Table XXXVI. D_R, L_{A1}=500ft, L_{A2}=500ft, Random Seed=42

Link	Lane	Density 1(veh/ln-mi)	
		V_F=5000vph, V_R=1000vph	V_F=3500vph, V_R=500vph
3	1	26.10	10.65
3	2	23.47	10.51
3	3	23.51	24.07
4	1	30.37	39.06
4	2	25.65	23.9
4	3	34.86	23.1
4	4	17.15	12.54
D_R		25.85	21.19

Appendix E. ANOVA Results

)	Anova: Two-Factor With Replication						
	SUMMARY	5000/1000	3500/500	Total			
	100/1300						
	Count	5	5	10			
	Sum	93.76	81.04	174.8			
	Average	18.752	16.208	17.48			
	Variance	4.35352	3.36547	5.228422			
	200/1100						
	Count	5	5	10			
	Sum	121.97	79.1	201.07			
	Average	24.394	15.82	20.107			
	Variance	11.15583	11.88245	30.65965			
	300/900						
	Count	5	5	10			
	Sum	134.78	79.69	214.47			
	Average	26.956	15.938	21.447			
	Variance	45.21403	3.47587	55.36116			
	400/700						
	Count	5	5	10			
	Sum	114.67	77.81	192.48			
	Average	22.934	15.562	19.248			
	Variance	33.79743	27.11682	42.16922			
	500/500						
	Count	5	5	10			
	Sum	140.2	75.82	216.02			
	Average	28.04	15.164	21.602			
	Variance	4.93565	16.67988	55.66006			
	Total						
	Count	25	25				
	Sum	605.38	393.46				
	Average	24.2152	15.7384				
	Variance	27.75547	10.55093				
	ANOVA						
	Source of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
	Length	115.8487	4	28.96219	1.788044	0.150267	2.605975
	Volumes	898.2017	1	898.2017	55.45244	4.51E-09	4.084746
	Interaction	155.597	4	38.89925	2.40153	0.065809	2.605975
	Within	647.9078	40	16.1977			
	Total	1817.555	49				

Figure 19. Two-way ANOVA Results

	Anova: Single Factor						
	SUMMARY						
	Groups	*Count*	*Sum*	*Average*	*Variance*		
	1400	5	93.76	18.752	4.35352		
	1300	5	121.97	24.394	11.15583		
	1200	5	134.78	26.956	45.21403		
	1100	5	114.67	22.934	33.79743		
	1000	5	140.2	28.04	4.93565		
	ANOVA						
	Source of Variat	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
	Between G	268.3054	4	67.07635	3.372146	0.029021	2.866081
	Within Gro	397.8258	20	19.89129			
	Total	666.1312	24				

Figure 20. One-way ANOVA Results for First Volume Set

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
1400	5	81.04	16.208	3.36547		
1300	5	79.1	15.82	11.88245		
1200	5	79.69	15.938	3.47587		
1100	5	77.81	15.562	27.11682		
1000	5	75.82	15.164	16.67988		
ANOVA						
Source of Variat	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	3.140376	4	0.785094	0.062787	0.992147	2.866081
Within Gro	250.082	20	12.5041			
Total	253.2223	24				

Figure 21. One-way ANOVA for Second Volume Set