Simulating the Impact of Traffic Calming Strategies

FINAL REPORT

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16. Abstract

This study assessed the impact of traffic calming measures to the speed, travel times and capacity of residential roadways. The study focused on two types of speed tables, speed humps and a raised crosswalk. A moving test vehicle equipped with GPS receivers that allowed calculation of speeds and determination of speed profiles at 1s intervals were used. Multi-regime model was used to provide the best fit using steady state equations; hence the corresponding speed-flow relationships were established for different calming scenarios. It was found that capacities of residential roadway segments due to presence of calming features ranged from 640 to 730 vph. However, the capacity varied with the spacing of the calming features in which spacing speed tables at 1050 ft apart caused a 23% reduction in capacity while 350-ft spacing reduced capacity by 32%. Analysis showed a linear decrease of capacity of approximately 20 vphpl, 37 vphpl and 34 vphpl when 17 ft wide speed tables were spaced at 350 ft, 700 ft, and 1050 ft apart respectively. For speed hump calming features, spacing humps at 350 ft reduced capacity by about 33% while a 700 ft spacing reduced capacity by 30%. The study concludes that speed tables are slightly better than speed humps in terms of preserving the roadway capacity. Also, traffic calming measures significantly reduce the speeds of vehicles, and it is best to keep spacing of 630 ft or less to achieve desirable crossing speeds of less or equal to 15 mph especially in a street with schools nearby. A microscopic simulation model was developed to replicate the driving behavior of traffic on urban road diets roads to analyze the influence of bus stops on traffic flow and safety. The impacts of safety were assessed using surrogate measures of safety (SSAM). The study found that presence of a bus stops for 10, 20 and 30 s dwell times have almost 9.5%, 12%, and 20% effect on traffic speed reductions when 300 veh/hr flow is considered. A comparison of reduction in speed of traffic on an 11ft wide road lane of a road diet due to curbside stops and bus bays for a mean of 30s with a standard deviation of 5s dwell time case was conducted. Results showed that a bus stop bay with the stated bus dwell time causes an approximate 8% speed reduction to traffic at a flow level of about 1400 vph. Analysis of the trajectories from bust stop locations showed that at 0, 25, 50, 75, 100, 125, 150, and 175 feet from the intersection the number of conflicts is affected by the presence and location of a curbside stop on a segment with a road diet.

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CHAPTER 1: INTRODUCTION

1.1. Overview

Traffic calming has its origins in the Dutch "Woonerf" schemes of the 1970's, and since then has been further expanded and spread throughout the northern Europe, but especially in Netherlands [1].However, it is still relatively new to many areas of Tennessee and the United States and it is not implemented to the extent of Europe. Traffic calming measures (TCM) are used for the purpose of reducing speed and regulating traffic volume to acceptable levels. These measures can have positive or negative traffic flow and safety impact to the community which is worth evaluating. If not properly implemented, traffic calming can lead to delays, traffic accidents, lower travel speed and overall dissatisfaction to the community. Traffic calming techniques can be grouped into two categories (1) non-physical measures such as educational programs and (2) physical measures which are of three types: horizontal measures which use forces of lateral acceleration to discourage speeding; vertical measures which use forces of vertical acceleration to discourage speed such as speed humps, speed tables etc. and narrowing which use a psycho-perceptive sense enclosure to discourage speeding. This study focused on simulating calming features that physically impact the drivers' speeds including (1) speed humps (2) speed tables and (3) raised crosswalks

Traffic calming is not only a transportation element to most communities but can be an enhancer of the safety of drivers and pedestrians, enhancing livability, improving air quality, change social behaviors and promote walkability, it is a great way of creating a sustainable city. The goal of this study is therefore to assess traffic calming programs through microsimulation in the context of urban transport system functioning with respect to the impact on modal split, routing decisions and in result, on observable traffic flows. As a result, this will help to properly represent the impact of engineering measures and the examination of speeds and travel times alterations for each type of measure are essential for livable communities.

1.2. Scope

To achieve primary aim of the study several primary tasks were involved: comprehensive literature search was undertaken to uncover published and unpublished reports and papers on Traffic Calming Schemes, programs and simulation. Selection of Study Segments, several roadway segments with known traffic calming in Metro Nashville area have been selected for the study. Traffic Calming Microsimulation which involves defining, simulating and evaluating the Impacts of Traffic Calming measures including raised Median Island, traffic circle, speed hump, raised crosswalk, crosswalk refuge etc. VISSIM software was used for simulation. Traffic Calming Sensitivity Analysis in which the impact of varying Traffic Calming were analyzed through simulation. The operational impacts from sensitivity analysis were documented and graphically plotted for comparison purposes.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Institute of Transportation Engineers (ITE) and Federal Highway Administration (FHWA) jointly published a report in 1999 [2] which defines traffic calming as the process which involves changes in street alignment, installation of barriers, and other physical measures to reduce traffic speeds and cut-through volumes in the interest of street safety, livability, and other public purposes. Effectiveness of traffic calming can be defined by reduction in the mean speeds; reduction in the 85th percentile speeds; reduction in the highest speeds. These reductions of speeds can lead to reduction in the number of complaints and inquiries in such a way that residents feel safer and there is an active response to public request. This effectiveness of Traffic calming measures can be judged by impacts of speed and traffic volumes. Based on *Traffic Calming: State of Practice* (1999), by Reid [2], speed impacts of traffic calming measures depend primarily on:

- Geometrics: Determines the speed at which the motorists travel through slow points
- Spacing: Determines the extent to which motorist speed up between slow points

These are two types of traffic calming policy that will be dealt in this study [3]: Black-spots approach (described as level 1/ level2) and area-wide approaches (described as level 3).Black-spot approach contributes to the reduction of vehicles speeds while Area-wide approach can lead to both reduction of speeds as well as volumes [3].There are numerous studies on "before" and "after" data of impacts on accident reduction. However, one should emphasize that analyses should be done in a greater scale to find the real impact of area-wide solutions [4]

The review of literature was done on both national and local basis. The literature review focused on "before" and "after" data for:
- 85th percentile speeds
- Average speeds
- Traffic volumes
- Traffic crashes

2.2 Traffic calming techniques

Traffic calming techniques can be grouped into two categories:

- Non- physical measures such as educational programs and enhanced enforcement.
- Physical measures such as speed humps, speed tables etc.

2.2.1 Non- physical measures

Education and enforcement: educating citizens and vehicle drivers about the impacts of traffic calming measures. In some places, education is used as a prerequisite before installing any device. This education is being given in different forms include:
Workshop include school programs, public outreach etc.
- Radar speed monitoring trailer, which display vehicles as they pass
- Speed feedback signs
- Enforcement by the police (traditional)

2.2.2 *Physical measures*

Physical driving techniques refer to the combination of measures that reduce the negative effects of motor vehicles use, alter driver behavior and improve conditions for both motorized and non-motorized users.

Traffic calming is very important especially in residential neighborhoods and small commercial centers. Traffic calming tools can be grouped in the following categories:

- Bumps, humps, and other raised pavement areas.
- Reducing street area
- Street closures
- Traffic diversions
- Surface textures and visual devices
- Parking treatments

Most often combinations of traffic calming techniques are used in road networks. Below is a brief description for some of onsite calming devices for reducing Speeds as were provided in FHWA [5].

Speed Hump: These are rounded raised area across roadway, typically 12 to14 feet in length and 3 to 4 inches high.

Speed Cushion: These are devices are typically 6 to 7 feet wide that allow most emergency vehicles to straddle the hump. They are more advantageous compared to speed hump when accommodating emergency vehicles.

Speed Table: A long hump typically 22 feet length with a flat section in the middle and ramps on the ends. Speed tables can be placed both in rural and urban areas.

2.3 National literature review

Traffic calming studies have been studied in different places in USA to check the effective processes used to plan and define a local traffic calming project as well as assessments of the effects of the individual and series of traffic calming measures. The following is a brief summary provided for various case studies done in USA [6].

- City of Wauwatosa(Wisconsin) Traffic calming study case
- City of Sunnyvale (California) Canary Traffic calming Case Study
- Portland (Maine) Traffic Calming Study-Massachusetts Avenue Neighborhood
- New York Neighborhood Slow Zone Program
- Seattle Safe Routes to School Program

Useful information concerning traffic calming devices was found on two significant resources:

- The federal highway Administration (FHWA)
- ITE

The literature search was also conducted on a comprehensive report prepared by Institute of Transportation Engineers (ITE) and published by the FHWA entitled *Traffic Calming State of the Practice (SOP)* [2], through which 20 communities were incorporated and selected on basis of broad objectives number and types of traffic calming measures, interesting institutional issues and availability of performance data. Therefore, the report is a very conclusive document that thoroughly reviews all aspects of traffic calming from a national perspective. Some of the municipalities in the plan include: Anchorage in Alaska, Temple in Arizona, San Jose in California, etc. Table 2.1 shows some data on the effectiveness of traffic calming devices.

Table 0.1: Traffic Calming Devices Impacts on Speed

Device	Sample size	85th Percentile Before Speed (mph)	85th Percentile After Speed (mph)	Average change in Speed (mph)	Average Percent Change
12- foot Humps	179	35	27.4	-7.6	-22%
14- foot Humps	15	33.3	25.6	-7.7	-23%
22- foot Tables	58	36.7	30.1	-6.6	-18%
Longer Tables	10	34.8	31.6	-3.2	9%
Raised Intersections	3	34.6	34.3	-0.3	1%
Circles	45	34.2	30.3	-3.9	-11%
Narrowing	7	34.9	32.3	-2.6	4%
One-Lane Slow Points	5	33.4	28.6	-48	-14%
Diagonal Diverters	7	29.3	27.9	-1.4	-4%

Source: FFWA/ITE: Traffic Calming: State of Practice [2]

Table 0.2: Traffic Calming Devices Impacts on Traffic Volumes

Device	Sample size	Average Change in Volume (Vehicles per Day)	Average Percentage Change in Volume (vehicles per Day)
12- foot Humps	143	-355	-18%
14- foot Humps	15	-529	-22%
22- foot Tables	46	-415	-12%
Circles	49	-293	-5%
Narrowing	11	-263	-10%
One-Lane Slow Points	5	-392	-20%
Full Closures	19	-671	-44%
Half Closures	53	-1611	-42%
Diagonal Diverters	27	-501	-35%

Source: FFWA/ITE: *Traffic Calming: State of Practice* [2]

Table 0.3: Traffic Calming Devices Impacts on Collisions

Device	Number of Sites	Average Annual Collisions[A]		
		Before Calming	After Calming	Percentage Change
12-foot Humps	50	2.62	2.29	-13%
14- foot Humps	5	4.36	2.62	-40%
22-foot Tables	8	6.71	3.66	-45%
Circles (without Seattle data) [A]	17	5.89	4.24	-28%
Circles (with Seattle data) [B]	130	2.19	064	-71%

Source: FFWA/ITE: *Traffic Calming: State of Practice* [2]
[A] Average annual number of collisions typically based upon a 12-month data collection period.
[B] Intersection collisions only.

From the FHWA/ITE manual it can be derived that the impacts of traffic calming devices are highly case-specific, depending on:

- Geometrics and spacing of measures
- Availability of alternative facilities
- Treatment of other facilities in area wide applications etc.

The FWHA/ITE report [2] further shows the impacts on traffic volumes are even more case specific than speed. Impacts on traffic volumes depend on the network of streets in the area, rather than the characteristics of the specific street itself. The availability of alternative routes and the application of other measures in area wide schemes may have as large an impact on volumes as do the geometrics and spacing of traffic calming measures. Moreover, the report suggested that it is difficult to draw conclusive results from traffic calming accident analyses because most safety studies do not account the influence of potential changes in accident reporting, weather conditions and traffic diversions.

2.4 Local literature review

In addition to conducting a review of national literature on traffic calming, an attempt was made to gather empirical results before and after studies in Nashville. Two reports were reviewed, namely Hillwood Neighborhood Traffic Calming Project- Follow up Study (2012) published by LLC and Metro Traffic Calming Study Phase 2 report which was prepared for Metropolitan Government of Nashville and Davidson County Department of Public Works in 2004, provided insight on local attempts at traffic calming. The purpose of follow-up study report was to evaluate the effectiveness of the implemented traffic calming plan after the measures have been in place for approximately 6 months. The report based on four major streets in the Hillwood Neighborhood where majority of the traffic calming measures were implemented also the speed and volume data for "before" conditions were available. These streets include Bresslyn Road, Brook Hollow Road, Hillwood Boulevard and Davidson Road. Table 2.4 to 2.7 lists local results from *"Hillwood Neighborhood Traffic Calming Project- Follow up Study"* [7].

The traffic calming devices presented in the literature review did reduce vehicle speeds and traffic crashes in the Hillwood neighborhood while volume data showed a fluctuation in daily traffic volume through the neighborhood over the last few years; however, this fluctuation does not indicate any significant changes in travel plans that could be attributed to the traffic calming devices. From table 2.5, the speed data comparison indicates that the 85th -percentile speeds were reduced in all four streets in both directions therefore the plan was successful in lowering the vehicular speeds on the residential streets. From table 2.6 the "before and after" comparison shows some fluctuation in traffic volume along the four streets in the Hillwood neighborhood. As shown in Table 2.7, fewer crushes occurred since the traffic calming devices were implemented than occurred 12 months before, however this is not enough to make comparisons of the "before" and "after" conditions because this study was done 6.5 months after placement of traffic calming devices therefore additional time and study is needed to support data-supported documentation of the safety impacts. As the primary objective of traffic calming is reduction of vehicular speeds, then based on the analysis of the data, it was concluded that Hillwood Neighborhood traffic calming plan was successful due to significant increase in the awareness of drivers to the neighborhood which has led to significant reduction in vehicular speeds.

Table 0.4: Neighborhood Traffic Calming Treatment by Street

Street	Traffic Calming Device/Technique	Count
Bresslyn Road	Choker/Chicane	2 pair
	Speed limit in pavement marking (30mph)	6
	Custom neighborhood traffic calming Sign	2
	All-way stop	1
Brook Hollow Road	Radar speed sign	2
	speed limit pavement marking(30mph)	3
	Speed limit signs	2
	Custom Neighborhood Traffic Calming Sign	2
	All-way stop	1
Hillwood Boulevard	Radar speed sign	1
	speed limit pavement marking(30mph)	3
	Custom neighborhood traffic calming Sign	3
	Change Yield Control to Stop Control	1
Davidson Road	Radar Speed Sign	2
	Custom Neighborhood Traffic Calming Sign	2
	All-way Stop	1
	speed limit pavement marking(30mph)	4
	Speed Limit Signs	8

Source: *Hillwood Neighborhood Traffic Calming Project- Follow up Study report* [7] page 1

Table 0.5: Speed "Before & After" Comparison

Street	Traffic Calming Measure	Direction	85th Percentile Speed (mph)			
			Before	After	Difference	% Change
Bresslyn Road	Chicane/choker & Speed Limit Markings	Northbound	44	39	-5	-11.4%
		Southbound	43	38	-5	-11.6%
Brook Hollow Road	Radar Signs & Speed Limit Markings & Stop Signs	Northbound	43	36	-7	-16.3%
		Southbound	42	37	-5	-11.9%
Hillwood Boulevard	Radar Sign & Speed Limit Markings	Eastbound	40	37	-3	-7.5%
		Westbound	39	38	-1	-2.6%
Davidson Road	Radar Signs & Stop Signs	Eastbound	39	38	-1	-2.6%
		Westbound	40	38	-2	-5.0%

Source*: Hillwood Neighborhood Traffic Calming Project- Follow up Study report* [7] page 2

Table 0.6: Volume "Before & After" Comparison

Street	Traffic Calming Measure	Direction	ADT Volume(vpd)			
			Before	After	Difference	**%** Change
Bresslyn Road	Chicane/choker & Speed Limit Markings	Northbound	313	470	157	50.2%
		Southbound	315	408	103	33.8%
		Total	618	878	260	42.1%
Brook Hollow Road	Radar Signs & Speed Limit Markings & Stop Signs	Northbound	1334	1353	19	1.4%
		Southbound	1611	1467	-144	-8.9%
		Total	2945	2820	-125	-4.2
Hillwood Boulevard	Radar Sign & Speed Limit Markings	Eastbound	2090	2253	163	7.8%
		Westbound	2095	2309	214	10.2%
		Total	4185	4562	377	9.0%
Davidson Road	Radar Signs & Stop Signs	Eastbound	2669	2240	-429	-16.1%
		Westbound	2884	2061	-823	-28.5%
		Total	5553	5553	-1252	-22.5%

Source: *Hillwood Neighborhood Traffic Calming Project- Follow up Study report* [7] page 4.

Table 2.7: Crashes Before & After" Comparison

Street	Segment	Number of Crashes			
		before	**after**	**difference**	**% Change**
Bresslyn Road	B/w Old Charlotte Pike & Davidson Road	**1**	**1**	**0**	**0%**
Brook Hollow Road	B/w Charlotte Pike & Davidson Road	**5**	**1**	**-4**	-80%
Hillwood Boulevard	B/w Charlotte Pike & Wilsonian Avenue	**10**	**7**	**-3**	-30%
Davidson Road	B/w Brook Hollow Pike & Harding Pike	**12**	**7**	**-5**	-41.6%

Notes:
1. Available "before" crash data included in 12 months of data. Available "after" crash data included 6.5 months of data.
2. It should be noted that one crash is counted for both Davidson Road and Bresslyn Road for the "after" condition since it occurred at the intersection of these two roads. Similarly, one crash is counted for both Brook Hollow Road and Bresslyn Road in the "before" condition since it occurred at the intersection of two roads. Two crashes are counted for both Davidson Road and Brook Hollow Road for the "before" condition since they occurred at the intersection of these two roads.

Source: *Hillwood Neighborhood Traffic Calming Project- Follow up Study report* [7] page 4.

2.5 Findings from Other studies

Aburahmah & Assar [8] evaluated if the installation of a physical measure such as a speed hump significantly reduces speed and traffic volumes. The paper describes the effects of different calming strategies on the traffic parameters such as volume, speed, and traffic safety. The installation of speed humps as a traffic calming measure proved to be effective at study locations. Similar study was conducted by Lee et al [9] in which they evaluated the effectiveness of various traffic calming measures from traffic performance and safety perceptive, and environmental and

public health impacts. Four calming measures were used to demonstrate its usefulness and applicability which were two types of speed humps, speed tables, and chicanes. Chicane was found to be better than other types of traffic calming measures considered, except in terms of vehicle emissions. They have resulted in a reduced effect on speed variation prior to the arrival to the SC compared to the humps. On another research, Petersen [10] found that the psychological traffic calming measures such as converging markings and lane narrowing had the least effectiveness, while the physical measures such as speed table and longitudinal channelizers had much more success in reducing speeds. Wei et al [11] found that when these calming measures are combined with other features like as a crest and a gentle bend they become more effective.

On the whole, there is abundant literature research exploring the impact that can result into installing various types of traffic calming measures [12] [13] [14] [15]. Most of these past studies conducted field experiments to examine traffic calming measures which were time consuming and expensive [16] [17].The time and data gathering constraints have led to the use of traffic simulation as an alternative approach to evaluate the operation of traffic calming features. Different simulation models which can be used to simulate the impact of traffic calming measures include: driving simulators and microsimulation models such as VISSIM and PARAMICS. The microsimulation models have been used to assess the impacts of various traffic calming measures with respect to driving behavior on isolated or area-wide traffic calming schemes. Through traffic simulation models, one can evaluate alternative calming treatments, test new designs, and conduct safety analysis with different calming features [18] [19] [20] .For instance, one study carried a three series of simulations to assess the impacts of road safety and level of service using VISSIM on a 1500m road link [21].The simulation reflected real field situation and found that the presence of humps caused travel time to increase and level of service to be reduced. In another research, Nair et al [22] found that the installation of speed breakers had no significant effect in reduction of accidents.

The use of driving simulators in assessing the impact of traffic calming measures has been highlighted in the past literatures [23] [24]. By using driving simulators, driving parameters, drivers' behaviors and infrastructural impacts can be examined under controlled environmental and traffic conditions without any disturbing factors. Some of advantages of driving simulators mentioned by [25] include: efficiency, low cost, efficiency, safety of the experiment, full control over all conditions, easy to collect data, and a proper verification of simulator's functioning in comparison with the field studies.
However, there are no abundant studies conducted to simulate the impact of traffic calming measures using VISSIM microsimulation.

2.6 Micro Simulation Models
Micro-simulation-based traffic models are becoming increasingly popular for the development and evaluation of a broad range of road of traffic management and control proposals in recent years [26]. Nowadays, many highway transportations micro-simulation software such as CORSIM, PARAMICS, VISSIM, AIMSUM, and among others have been made available on the market and are used as tools for the evaluation of traffic management and control. Due to their ability to simulate the behavior of individual vehicles within a predefined network, they allow traffic engineers and planners to assess the performance of existing roadway systems in a detailed manner as well as to predict the effects of operational or infrastructure changes [27]. Various elements of

traffic calming such as street closures, one-way streets, road diets etc. can be represented in microsimulation models. Also, restrictions such as intersection diverters and median barriers which naturally impact on the volume control can easily be modelled. As the purpose of microsimulation modelling is to produce traffic conditions as realistically as possible [28], thereupon, many transportation researchers have utilized microscopic traffic simulation tools to model performance of facilities in the state [28] [29].

This chapter is focused on PTV VISSIM, the software used in this study to perform the simulation. VISSIM is a microscopic time step and behavior-based simulation model. It was released in 1992, a microscopic simulation model and a component of the PTV vision suit developed in Germany [30]. VISSIM explicitly simulates the behavior of individual vehicles and their interactions [21]. It is the most powerful tool available for simulating multi-modal traffic flows, including cars, trucks, buses, heavy rail, trams, LRT, bicyclists and pedestrians [31]. It can also interface with a number of transportation engineering and planning profession programs. Due to its flexibility in network structure it gives the user the confidence to know they can model any type of geometric configuration or unique operation/ driver behavior encountered within the transportation system. Despite the advances in computing power and the ability of available simulation tools to represent complex driver behavior, simulation modelling and analysis requires extensive field data for validation-calibration [27]. Model verification, calibration, and validation are very important steps to ensure reliable information is gathered from the model. Various parameters that can be calibrated in VISSIM are acceleration, desired speed, emergency stopping distance, waiting time before diffusion and other Wiedemann parameter [31].In this study, desired speed is an important parameter that has a significant influence on achievable travel speeds, roadway capacity and travel time at the traffic calmed network. Therefore, the desired speed in VISSIM was calibrated and validated.

The quality of traffic flow model, which describes the movement of vehicles in the network, is important for the quality of simulation itself. Instead of using simpler model which make assumption of a constant speed and a deterministic process of vehicle arrival, the model of Wiedemann was used. This model is known for its extensive use in the VISSIM microscopic multi-modal traffic flow simulation software [32].The micro simulation can be used to obtain the distribution of speed and distance between the vehicles for various traffic volumes with and without installation of traffic calming devices

2.7 Impact on Capacity
Highway Capacity Manual (HCM) defines capacity as the maximum flow rate which can reasonably be expected to traverse a point or a uniform segment of a lane during a specified time interval under prevailing roadway, traffic, and control conditions [33]. While there is a plenty of literature with traffic calming themes, very few have focused on the impact of calming features to residential roads capacity. For instance, Garcia et al. [34]studied the evaluation of effects of the type and spacing of traffic calming features on capacity using microsimulation software .The capacity of road section varied between 810 and 1300 vehicles per hour per lane (vphpl) with traffic calming features placed at varying spacing from 25 to 400m. Another study found that TCMs have a direct effect on network capacity and changing in the number and location of measures can change network capacity [35]. García et al [34] used average delay to determine capacity of an existing traffic flow from which average delay increased exponentially. The

interesting part of this study was the estimation of the capacities factoring the presence of calming features. In another study, multi- regime model with different state equations was developed by May and Keller [36] for investigating relationships between macroscopic and microscopic flow models (car-following models). In this paper, the Wiedemann 1974 driving model for urban (motorized) roads was used as capacity is not defined as the single highest flow level ever expected to occur on a facility. Rather it is a value that represents a flow level that can be reasonably achieved repeatedly at a given location and at similar locations [37]. Therefore, capacity in VISSIM is estimated by considering the car following algorithm which deal with individual space and speed of vehicles tending to maintain elements of headways and safety distance. The models were used because they provided the best fit (R^2) in comparison to other fits such as Greenshields [38], Greenberg [39], Drew model *(18),* Underwood model [40] and the Drake et al. model [41].

In evaluating the traffic calming features, the best fit for speed-density curve is secured, and then steady state equations are employed to derive flows which are subsequently used to yield the speed-flow diagrams. These flow diagrams are macroscopic traffic model used to predict the capacity. Specifically, in this study the speed-flow curves generated were used to predict precise capacity influenced by the type of calming features on residential roadways. Earlier studies showed that the estimated capacity is sensitive to two the parameters; additive component of safety distance and multiplicative element of safety distance [42]. Therefore, these parameters need to be calibrated to better replicate field traffic flow behavior. In this study, a capacity estimation approach which uses speed-density and speed-flow relationships in the microsimulation is presented. The study evaluated through microsimulation the impact of different traffic calming to the traffic flow characteristics along selected roadway segments in Nashville, Tennessee. VISSIM speed reduction zones were used to model traffic calming effects copying from Lee et al. [43] who also considered alternative way of representing traffic calming using a function called "reduced speed areas" in VISSIM

CHAPTER 3: METHODOLOGY

3.1 Research Area

The main research focused on Oakhill Valley Lane road which is a two-lane residential street located in Nashville, Tennessee, Figure 3.1. The study investigated speed humps, speed tables and raised crosswalks. The calming devices in this area have been implemented to reduce the effects of speeding and cut-through traffic in the residential neighborhood for which has led to safety increase to the community living in the residence. As major roadways and intersections in Nashville become more congested, there is a tendency of impatient drivers to use residential streets for trespassing in order to avoid congestion. All streets used in this study were local residential streets and they do not experience large traffic volume during the day. Free-flow speeds conditions exist throughout during the day. Therefore, GPS are appropriate devices used to collect spot speed data. In the selected residential road the following features were found (1) Intersections regulated by a stop sign (2) Normal crosswalk and raised crosswalk (3) Speed limits signs: 30 mph and 15 mph in the vicinity of calming devices (4) Speed tables and speed humps (5) A Gate to regulate trespassing vehicles after hours (6) Off street parking.

Figure 0.1: Oakhill Valley Lane Road (Google)

3.2 Data collection

Before the actual traffic data collection, preliminary studies and pilot testing were conducted through the use of internet and site reconnaissance. Basic information such as location and name of a roadway segment, geometry of the road (dimensions, types and location of calming devices), and environment were found. Also, several trial runs were conducted to confirm whether the working devices such GPS work efficiently and determine their accompanied challenges.

Field data collections fell into two main types and include the following:

- Traffic Volume Counts
- Speed data collection

3.2.1 Traffic Count

The Miovision Scout unit [44] was used to measure traffic flow per lane. The Miovision Scout unit is a traffic-counting device with video recording attributes that count and classify traffic per lane. This camera system was mounted on a stand with its top camera directed toward one direction of traffic, fixed at sidewalk rails, looking down on traffic. The camera was set up to record vehicles in all lanes, moving in both directions. Figure 3.2 shows the Miovision Scout system and its stand

[44]. Data were collected for 12 hours period during weekdays between 7 am and 6 pm. Data were extracted and screened for analysis and VISSIM simulation.
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Figure 0.2: Miovision Scout (Traffic Counting Feature)

3.2.2   GPS Data

A portable Wide Area Augmentation System (WAAS/EGMPS) enabled USB GPS Receiver was used to collect second-by-second vehicle trajectories along the road segment [45].The GPS provides positional horizontal accuracy up to 5 meters 3D RMS, velocity accuracy of 0.1m/sec and time accuracy of 1 micro-second synchronized to GPS time. Figure 3.3 illustrates a diagram of speed profiles provided by a GPS receiver before and after passing the calming features along the study segment. As shown in Figure 3.3, vehicle speeds were influenced by the presence of traffic calming features and 40 speed profiles were collected from test vehicles**.** GPS feature used on a test vehicle recorded vehicle position (latitude and longitude coordinates) and speeds at a specified 1 second intervals. GPS determined test vehicle position and speed using signals from earth-orbiting satellites. Th**e** GPS data collection was conducted on weekdays (at the same time the volume data were collected). Ten different drivers without prior knowledge about the objectives of the study drove the test vehicles embedded with the GPS in which each driver made a complete round trip providing a total of 40 trips. Free flow speed conditions were used to ensure that the impacts on test vehicles speed were influenced only by presence of calming features. The GPS data were screened whereby 10 runs from GPS equipped test vehicles were removed (debugged) from analysis due to non-free flow conditions, presence of stopping vehicles due to interactions with pedestrians and poor signals from satellites, which resulted to abnormal speeds, accelerations or decelerations. Therefore, only 30 simulation runs were retained for further analysis and evaluation in VISSIM. Figure 3 shows four speed profiles along the study segment that include three speed humps adjacent to each other. Only speed hump 2 was used to characterize the behaviors of drivers when crossing speed humps. The driving patterns of speed hump 1 were discarded as they were influenced with closeness of nearby crossing street. Speed hump 3 was discarded because it was located at a very close distance to speed hump
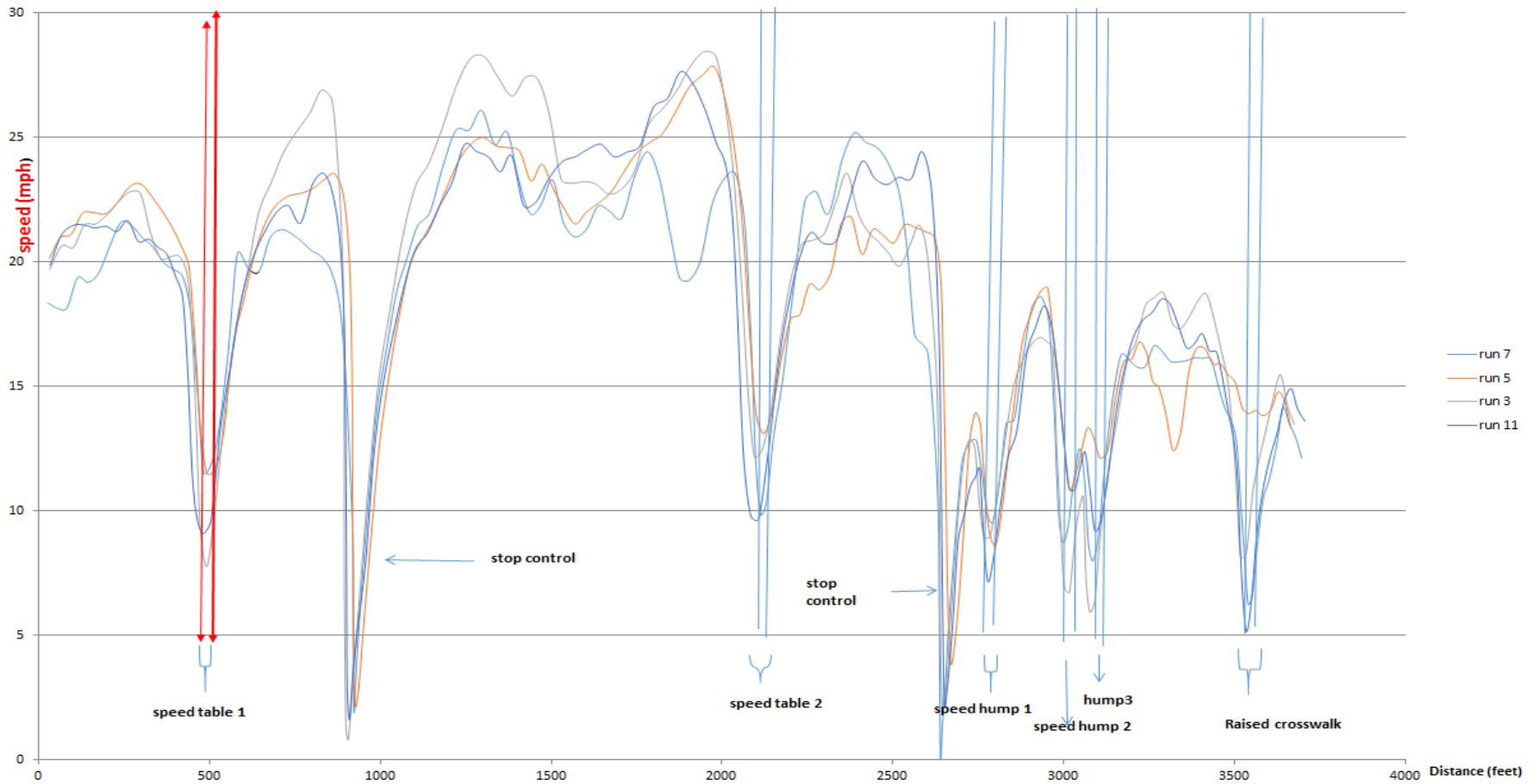
Figure 0.3 : GPS Speed profiles Samples from Oak Hill Valley Lane Study Segment

3.3 Speed Analysis

Speed percentiles were used to determine effective speed distribution for desired speeds of vehicles in VISSIM. Desired speed is defined as the speed the driver would choose in absence of any restrictions imposed by other vehicles or by traffic control devices. A frequency distribution table was used to determine speed percentiles. 50th and 85th percentiles are the two most common percentiles, but in this study seven percentiles were defined to accurately match simulated and observed speed at the approach and exit of the traffic calming devices. The minimum, 7th, 15th, 50th, 85th, 95th and max percentile speeds were used to assign percentiles from field as input in the desired speed distributions [34]. The 50th percentile is the average speed of drivers in the traffic stream while 85th percentile is the speed at which 85 percent or below of drivers drive at [46] .The following formula was used to calculate respective percentiles:

$$S_D = \frac{P_D - P_{min}}{P_{max} - P_{min}}(S_{max} - S_{min}) + S_{min}$$

Where: SD = speed at PD, PD = percentile desired, P_{max} = higher cumulative percent, P_{min} = lower cumulative percent, S_{max} = higher speed, and S_{min} = lower speed.

The cumulative speed distribution curves from data collection in field were plotted and inputted manually in VISSIM to match the desired speeds at reduced areas. Table 9 and 10 and their respective figures 3.4 and 3.5 show the percentiles of speeds at the two speed tables (table 3.1 and table 3.2).

Table 0.1: Percentiles of speeds at reduction area (first speed table)

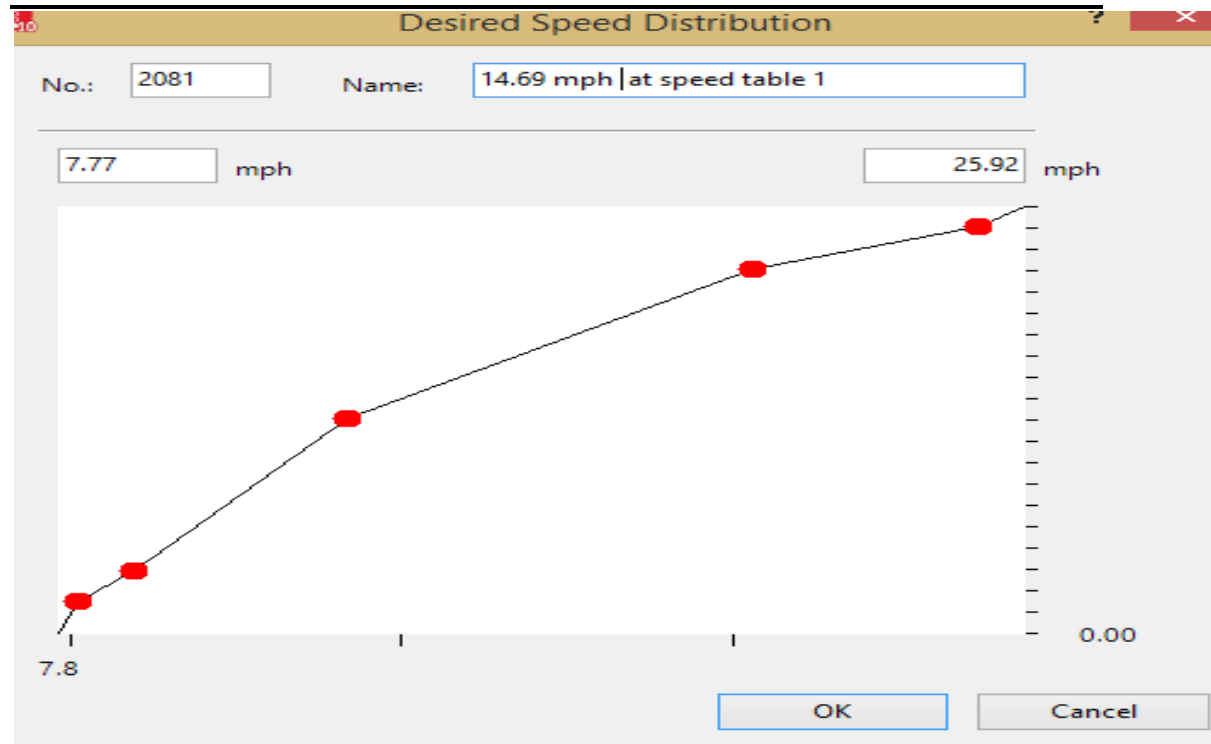| Percentiles	1	7	15	50	85	95	100
Speed(mph)	7.78	8.89	9.98	13.27	20.78	25.03	25.92

Figure 0.4 desired speed distribution for vehicles at the first speed table

Table 0.2 Percentiles of speeds at reduction area (second speed table)

Percentiles	1.00	7.00	15.00	50.00	85.00	95.00	100.00
Speed(mph)	9.81	9.82	9.93	14.20	21.02	24.84	25.25
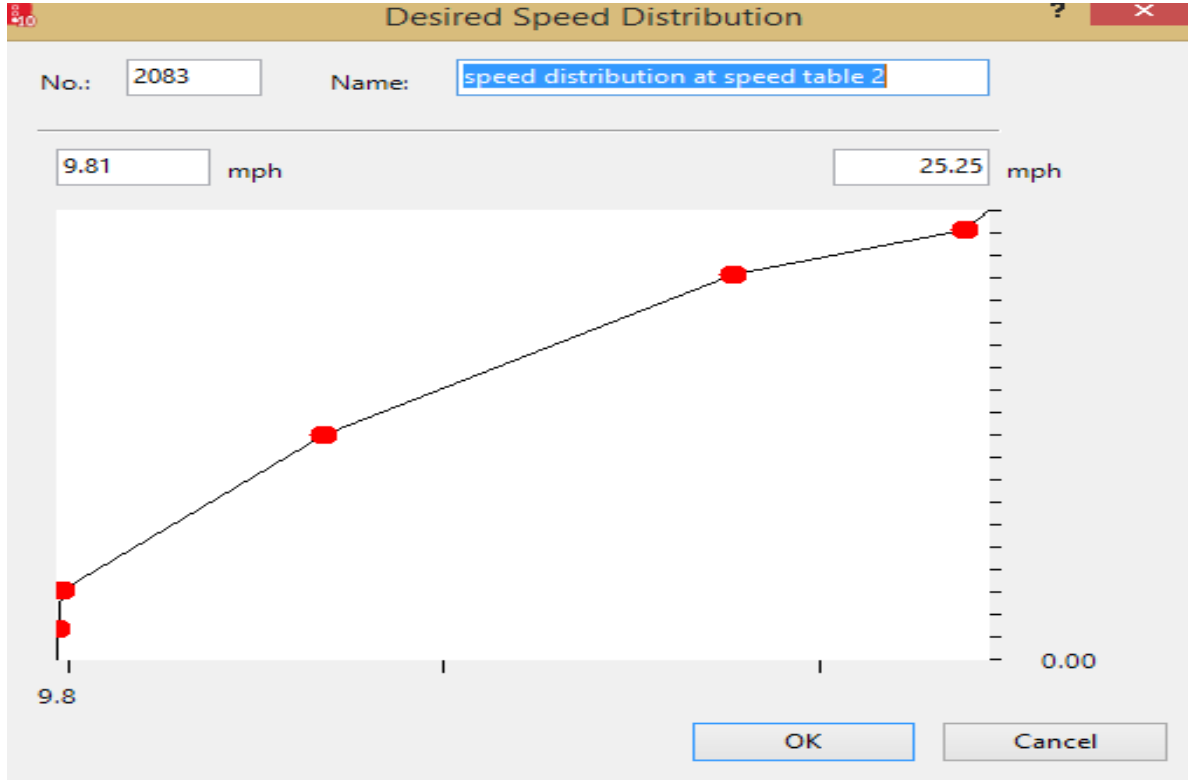
Figure 0.5 desired speed distribution for vehicles at the second speed table

3.4 Microsimulation

Microsimulation software VISSIM developed by PTV was used to replicate individual vehicle movements on a second-by-second basic to assess traffic performance due to presence of calming devices on roadways [30]. Vehicle classes, road geometry, hourly volume and aggressiveness of drivers were defined to represent the driving behavior when cross the calming features. To mimic the variability of drivers in the field, the microscopic model was run in multiple times for the roadway segments and the analysis section developed. Due to the variability of drivers' characteristics, minimum numbers of runs were computed at 95 per cent confidence level to represent the desirable traffic conditions in the field [47].

The following were the procedures taken to develop a base VISSIM model:

1. Network development: this included creating background images using a scaled google map and link modelling. The following is a detailed explanation on how they were done in VISSIM:
    *   Creating Background images. VISSIM software allows user to insert true to scale digital maps as a background image for a detailed VISSIM network model as graphic files. Therefore, images were taken (screenshot) from a google map and saved as *.png graphic

15

file format. Using the background image toolbar from the network objects, the images were loaded, scaled and arranged in the Network Editor [30]

- Modelling of links. Links were modelled based on the geometry of the road network as shown from the background images inserted. Length of the link is defined based on the scaled background images; link behavior type is set to Urban (motorized). Links were connected using connectors. With connector window, both change distance per lane and emergency stop distance were set.

2. Provision of traffic controls

There was a need to assign desired speed decisions on links and connectors based on the desired speed distribution for controlling the vehicle's approach speed and lastly define reduced speed areas with its appropriate desired speed. The following is a detailed explanation on how they were conducted in VISSIM.

- Assigning desired speed decisions on links and connectors. After modeling links the next step was to assign desired speed decisions on links and connectors using desired speed distribution defined based on vehicle classes [30].
- Defining reduced speed areas. Reduced speed areas are assigned to the link or connectors to modify the assigned desired speed. This is a useful network object, especially for the left and right turning vehicles at the intersection. Reduced speed areas can be defined, and the desired speed can be assigned based on vehicle class in interest. In the reduced speed area, speed assigned can be higher than the desired speed and vice versa [30].
-

3. Modeling vehicle routes and routing decisions

In VISSIM vehicular traffic can be modeled by assigning either static routes partial route, Partial PT, Parking lot, or Managed lanes which define the routing decisions and therefore specify the paths which the vehicles travel in the network [31]. In this study only, static route was used to define the routing decisions from a routing decision point "From Section with a default color Purple" to its end at a so called "To Section with a default color Turquoise". These static routes were defined to route vehicles using a static percentage for each destination [30].

4. Modeling vehicle compositions

Based on the traffic counting data collected, vehicle compositions from the vehicle type for all approaches at the intersection and road segments were calculated and assigned in the model so that the vehicle can be generated accordingly [30].

5. Modeling Driving behavior

In modeling the driving behavior, the VISSIM software uses two Wiedemann car-following models: Wiedemann 74 for arterials and Wiedemann 99 for freeways. As the scope of this study covers only the arterial roads, Wiedemann 74 car-following model was used.

6. Defining vehicle inputs

Another step in developing the base model was to insert the vehicle volumes based on the field traffic counting data collected. Vehicle inputs control the number of vehicles which are fed into the VISSIM network developed. Each vehicle input was defined by time intervals and the corresponding vehicle composition was selected.

3.5 Modelling reduced speed areas:

In order to model traffic calming features in VISSIM, speed reduced areas and desired speed decisions were used, see figure 3.6 below. These areas make vehicles decelerate at a constant (user

defined) rate and at a desired speed just before entering the zone. For permanent speed settings, desired speed decisions were used (yellow bar). Desired speed decisions make vehicles slow down after crossing the yellow bar. To reduce the speed of a vehicle at the same time make them slow down before crossing the desired speed decision (yellow bar), a short reduced speed area (yellow box) was then placed just upstream of the desired speed decision point. The lengths of the reduced speed area were defined as well as deceleration and acceleration profiles on the approach and exit. Length of calming features in VISSIM varied depending on type of calming feature simulated and the reliability of data heavily depended on calibration. Speed percentiles collected from the field using GPS receiver were used to determine effective speed distribution for desired speeds in VISSIM. The minimum, 7th, 15th, 50th, 85th, 95th and max percentile speeds were used to assign percentiles from field as input in the desired speed distributions [34]. Also, for each field run, acceleration and deceleration rate of a vehicle were calculated followed by the mean values for different speed calming features at the approach and exit of respective reduced speed areas in VISSIM. Tables 3.3 summarizes the descriptive of GPS captured speed data across the calming features indicating speed humps had the lowest average speed while speed table 11 had the highest average speed. Speed humps recorded the lowest average deceleration while speed table 2 recorded highest values of deceleration. Simulated vehicles' deceleration rates are important for each calming feature as they represent driving behaviors in evaluating of traffic calming features [43].
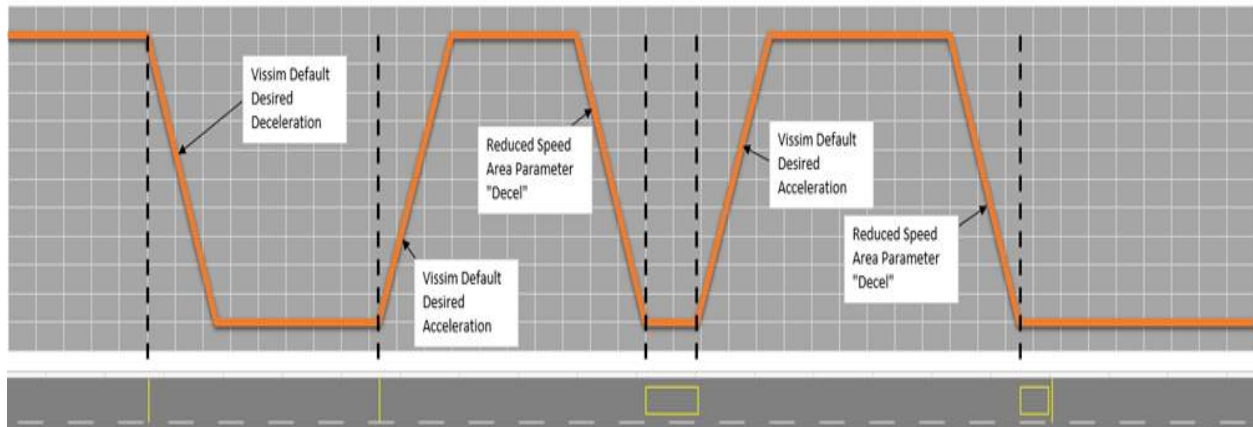
Figure 0.6 Modelling of Traffic Calming (Reduced Speed Areas and Desired Decisions)

Table 0.3 Descriptive statistics for each calming feature analyzed

	Statistics	Speed table 1 (17-ft)	Speed table 2 (21-ft)	Speed Hump	Raised Crosswalk
Speed (in mph)	Average	14.66	15.42	13.6	14
	Standard Deviation	5.238	4.61	4.12	5
Deceleration (in ft/s²)	Average	3.44	4.52	2.43	1.28
	Standard Deviation	1.08	0.974	4.12	0.676

3.6 Model Calibration

Calibration of the model ensures the model reflect the real-world conditions. Calibration of the model fell into three main types and includes the following: (i) Number of simulations runs (ii) volume Inputs (iii) speeds calibration.

3.6.1 Number of simulations runs

The required multiple runs with default parameter were determined in the model by defining an adequate vehicle travel time section and then, four initial simulation repetitions were executed. Sample standard deviation was computed using average travel time per section for all four preceding runs with a random seed increment step of 1. The minimum repetitions were computed using the formula below at 95% confidence level [47]

$$C = 2 * t_{\left(1-\frac{\alpha}{2}\right),N-1} \frac{s}{\sqrt{N}} \qquad (3.6)$$

Where: C = 1−Confidence Level,

$t (1-\alpha/2)$, N-1 is a t-statistic value for the probability of a two-sided error summing to alpha with N-1 degrees of freedom. Minimum of 10 simulation runs were found to be enough for the simulation model.

3.6.2 Volume Inputs

The number of vehicles (vehicles/hour) recorded in field were inputted in VISSIM for simulation. To ensure that a model reproduces a well reasonable real-world traffic volume as assigned, Geoffrey E. Havers developed a continuous volume tolerance formula known as GEH Formula. This formula was used to compute GEH statistic and a value less than 5 was accepted.
For hourly traffic flows, the GEH formula is:

$$G_H = \sqrt{\frac{2(m-c)^2}{m+c}} \qquad (3.9)$$

Where:
m is the traffic volume from the traffic model (vehicles per hour)
c is the real-world traffic count (vehicles per hour).

Table 0.4: GEH computations

street names					
From	**To**	**observed count**	**simulated count**	**GEH**	**Decision**
Oak Hill School	Robertson Rd &Van Lee Dr	36	28	1.41	Acceptable
Oak Hill School	Churchwood Dr	72	85	1.47	Acceptable
Robertson Rd &Van Lee Dr	Oak Hill School	75	82	0.79	Acceptable
Churchwood Dr	Oak Hill School	48	49	0.14	Acceptable

3.6.3 Speeds calibration

Figure 3.7 presents speed profiles along study roadway segment with calming features. As shown, speed decreased to its minimum at the calming features locations then increased to maximum speed values. Influence zones can also be determined from the graphs, which are areas over which traffic calming features produce a reducing speed effect. For instance, drivers approaching the calming features started to reduce their speeds at 220 ft, 100 ft, 30 ft, and 50 ft from speed table 1, speed table 2, speed hump and a raised crosswalk respectively. The reduction area for speed hump was relatively short compared to other calming features. Microsimulation model was calibrated to ensure the model represents the observed traffic behavior as in field. Different parameters and variables were adjusted to match the realistic conditions. The adjusted data include volume, speed distribution, traffic composition etc. Before evaluating various scenarios of calming measures in VISSIM, simulated and observed data were compared.

It is evident from Figure 3.7 that the speed profiles for both simulation and field matched. The patterns were similar for each respective calming measure type. For accuracy, average speeds of simulated and observed data were computed and compared. As shown in Table 3.5, difference in average speeds between the simulated and observed data are less than 1% for all types of traffic calming measures. Also, based on t-test results, the difference between observed and simulated speeds at all calming features were found to be statistically insignificant.

**Table 0.5: Calibration results between the simulated and observed data**

	Speed table 1	Speed table 2	Speed hump	Raised crosswalk
Average speed (in mph)				
Observed	14.66	15.42	13.6	14
Simulated	14.64	15.39	13.55	13.9
Difference (%)	0.14	0.19	0.37	0.71

3.7 Model Validation

After the calibration of the model, the model was validated using travel times collected on different weekdays using test vehicles equipped with GPS. Validation is the process of testing whether the calibrated model represents a viable and useful alternative means to real experimentation. First, we started with visual validation; this was done by inspecting the graphical presentation of the modelled network as the model runs, trying to spot any unusual behavior [48]. All the major problems were removed from the model. However; this cannot replace a more quantitative validation. Therefore; travel time data was collected in different weekday using testing vehicles which were then compared with average simulated travel times. Percent error was used to calibrate the model [49] .The formula can be applied either to a single pair of observed-simulated measurement or to aggregate network wide measures. From the table 3.6 below it was noticed that the average difference in travel times in VISSIM model from field were below 15% indicating a reasonable matching between the simulated and observed travel times. Generally, all validation results for the two directions (NB and SB) were satisfactory with minimal errors. Therefore, it was concluded that the model was well calibrated and validated.
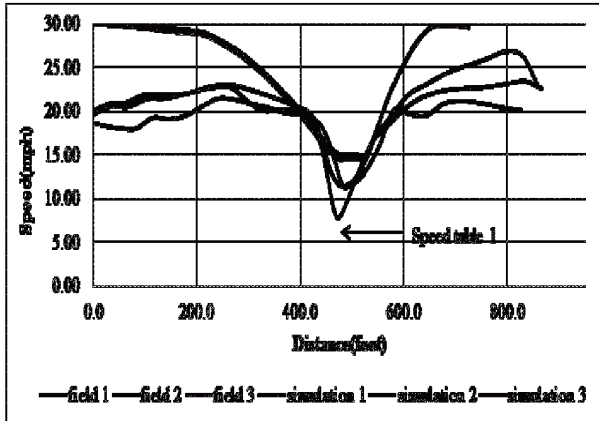
Scenario 1: Speed table 1
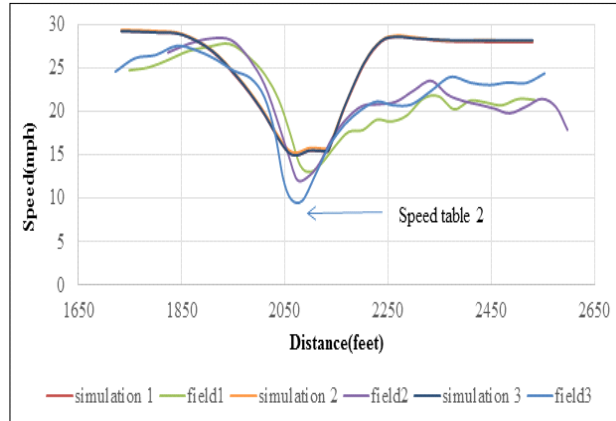
Scenario 2: Speed table 2
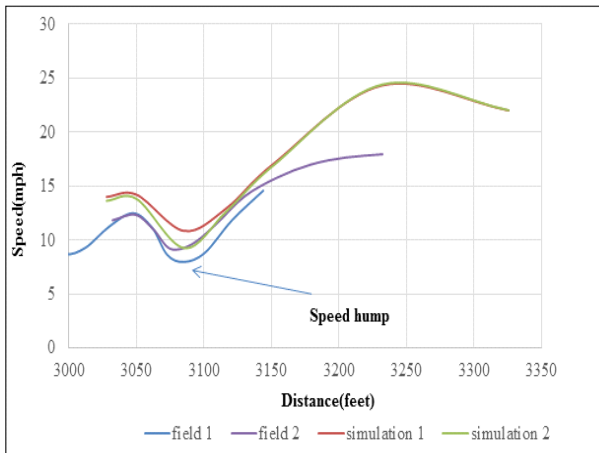
Scenario 3: Speed hump
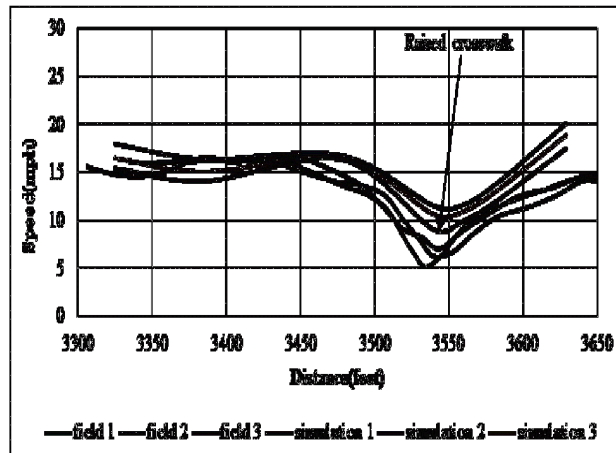
Scenario 4: Raised crosswalk

Figure 0.7 Examples of speed profiles for observed and simulated data

Table 0.6 Validation Results using Percent Error (PE)

VISSIM Calibration Runs		
Travel time Run	NB Travel Time (s)	SB Travel Time (s)
1	128.3	129.12
2	127.38	122.41
3	125.48	127.21
4	131.13	130.47
5	128.85	128.26
6	130.44	126.89
7	128.93	126.83
8	131.19	130.41
9	129.78	127.74
10	127.91	128.87
Average TT	128.94	127.82
Min TT	125.48	122.41
Max TT	131.19	130.47
Average Speed(mph)	19.4	19.6
Average TT Difference from field	-6.94	-13.47
% Difference	5.7	12.1

3.8 Simulated Scenarios

A road link of 5250 feet was built in the simulation environment, and the devices were placed in the analysis section in different distances from each other. Five series of simulations were carried out for five different configurations:

- Without calming devices
- Speed table 1(17-ft wide table) installed
- Speed table 2 (21-ft wide table) installed
- Speed hump installed
- A raised crosswalk installed

For each type of scenario, simulations were conducted with 9 different traffic volume accessing the road, input flow volumes were assigned from 100 to 1700 vehicles per hour per lane in the increment of 200. The case of free flow (no calming devices) is simulated as the base case for all 9 flow conditions. For each type of scenario, a vehicle travel time measurement was placed in upstream of the calming device at approximately 385 feet then the destination was placed at approximately 300 feet after the device(s). Distances and travel times were recorded in the travel time sections and, were used to compute the average speed for individual vehicle per each volume. The minimum distance between calming features was computed to ensure drivers regain their average speeds before crossing the next calming measure. This was considered in order to avoid the possibility of short distance between two calming measures in which the previous calming feature influencing the next measure. The maximum speed of drivers is a speed limit of 30 mph and the minimum speed required to cross the calming device was 6.92 mph. Minimum distance was calculated based using the formula:

$$\frac{V^2 - V_0{}^2}{2a} = S$$

For values of V_o and V equal to 6.92 and 30 mph respectively, and "a" is the acceleration (2.5m/s^2 for passenger car), a value of S = 111.65 feet is obtained. Traffic calming features were therefore coded and placed at least 111.65 ft from each other to ensure a desired speed is achieved. In this research, 350 ft was set as the minimum distance between calming measures. For each type of traffic device, 3 spacing were simulated: 350, 700 and 1050 feet. 9 different traffic flow levels were considered from 100 to 1700 vehicles per hour per lane in the increment of 200.

3.9 Capacity estimation

The simulation runs were performed along the 5250 ft study segment based on default values of driving behavior parameters but initially without the presence of calming features. Using simulation generated data, the speed-flow curves were developed, and the capacity was estimated. Initially, higher values of flows were obtained from the simulation compared to field conditions (possible traffic volume without presence of calming features). This implied that drivers were aggressive than normal. A proper calibration of parameters was therefore conducted which involved fine-tuning of safety distance parameters until the model output capacity was close as possible to the field capacity. Calming scenarios were coded in calibrated models that were used to generate flow-speed-density relationships. The speed-density curves resulting from calibrated VISSIM model were first developed and used to derive mathematical models which best suited the data. The steady state equations i.e. Flow (Q) = Speed (U)*Density (K) were used to estimate relationships as shown in equations (1) and (2). The algorithms developed were applied to fit the simulated data [36].Research has shown that macroscopic models can successfully be developed

from generalized car following equations whenever suitable values of the distance between the headway exponent in equation (l) and the speed exponent (m) are chosen [50]. May and Harmut [36] investigated the relationship between macroscopic and microscopic models in which they proposed a method to obtain non-integer values of m and l exponents of the general car-following model. This model describes speed U as a function of density K as:

$$U(K) = (U_f^{1-m} + c. K^{l-1})^{\frac{1}{1-m}} \qquad (1)$$

Where:
U_f is the, free-flow speed
K is traffic density, and
l, m and c are model parameters representing the distance headway exponent, speed exponent and appropriate constants consistent with physical restrictions respectively. All these parameters together with Uf should be calibrated according to simulated results. By using speed-flow-density relationship, Q=UK, the flow was obtained as follows:

$$Q = K \cdot (U_f^{1-m} + c. K^{l-1})^{\frac{1}{1-m}}$$

CHAPTER 4: RESULTS

The results from four different scenarios; speed table 1, speed table 2, speed hump and a raised crosswalk, are presented to illustrate the impact of traffic calming on vehicle speeds and capacity.

4.1 Speed Results

Number of vehicles that passed over calming devices in a predefined 5250 feet section in VISSIM was compared with expected number of vehicles to pass over calming devices. Figure 4.1 below illustrates the comparison of input flow and expected flow. At 1180 vphpl the capacity of the facility was reached. At this instance, the v/c is equal to 1. This analysis was very important in speed and travel time computations to avoid delay caused interactions between vehicles at high flow levels. For flow less than 1180 vphpl, the output flow remains the same as the input flow, irrespective of spacing of calming devices. At higher flows beyond capacity of the facility vehicles are removed from the system after 1 hour of simulation which leads to higher variations between the input flow and expected flow.
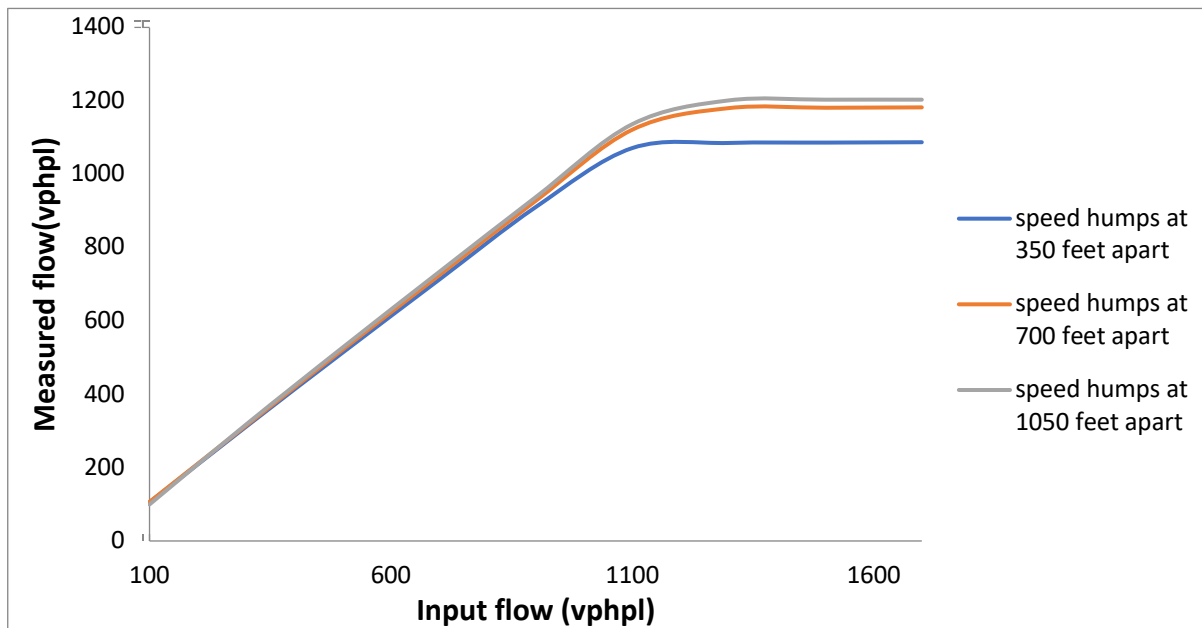
Figure 0.1: comparison of input flow and expected flow

Speeds were analyzed to study whether; the presence of calming devices had impacts in reduction of speeds. Figure 4.2 below illustrates the variation of mean speeds with presence of calming devices at different spacing apart. The speed limit was set to 30 mph. Hence, the base case under no traffic calming shows a mean speed of 30 mph. As flow increases the reduction in speeds decreases but the reduction in speeds is relatively insignificant compared to when calming devices are present. The minimum spacing used in the simulation to achieve desired speeds of 350 feet was used. From the graph, it is evident that when the traffic volume is above 1180 vphpl speed reductions are more pronounced. This is due to both presence of calming devices and vehicles held up in queue. At input flow below the 1180 vphpl, vehicles cross over speed tables at lower mean speeds compared to other spacing.

One way-between group analysis of variance was conducted to explore the impact of mean speeds due to presence of calming devices at varying spacing. Scenarios were divided into three categories

350 feet apart, 700 feet apart and 1050 feet apart. The One-way ANOVA procedure produced a calculated p-value of 0.0001 which is less than the reference p-value of 0.05. This result suggests that one must reject the null and accept the alternative hypothesis that the mean speeds of the scenarios are different according to spacing apart. Statistically, this means that there was a significant difference in mean speeds for all three scenarios. Also, Post-hoc comparisons for mean speeds at 350 and 700 feet apart using LSD produced a calculated p-value of 0.001. Statistically, this means that there was a statistically significant difference in mean speeds for calming devices at 350 and 500 apart. The same applies to mean speeds for 350 feet and 1050 apart. Generally, for all scenarios, reduction in speed increases when the spacing between speed tables is close. The likely points to achieve minimum speed assumed to be at the measure. However, not all drivers achieved minimum speed at the measure as it was seen from individual speed profiles developed from GPS data. Some minimum speeds occurred before or after the midpoint of the respective traffic calming.

Figure 4.3 illustrates the mean speed reductions due to traffic calming measures; it was found that that spacing was a key parameter for average travel speeds of cars. The impacts of speed humps and raised crosswalks for 350 feet spacing are almost similar while for the speed tables 2 for the same spacing, they caused the lowest reduction of speed of drivers of about 47%. And, when the spacing is 1050 ft, drivers experience the lowest reduction in speeds for speed table 2. Recommended spacings to attain desired street speeds were calculated from Speed-Spacing model which developed from the calibrated VISSIM model (Fig. 4.4). Therefore, in order to maintain mean speeds below 15 mph, spacings should not exceed 430 feet, 265 feet, 550 feet, 630 feet for 17-ft speed tables, 21-ft speed tables, speed humps and raised crosswalks respectively.
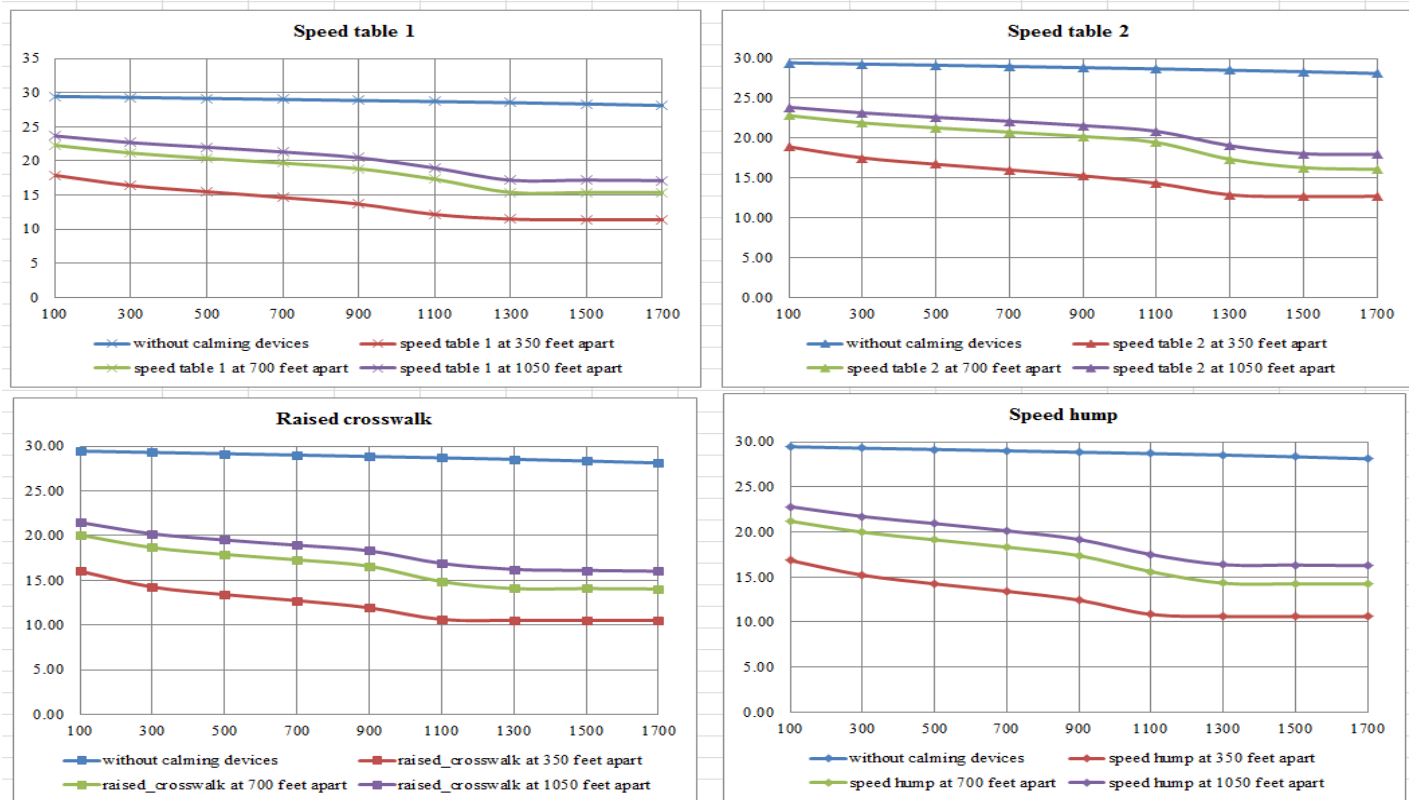
Figure 0.2: Impact of calming measures on mean Speed
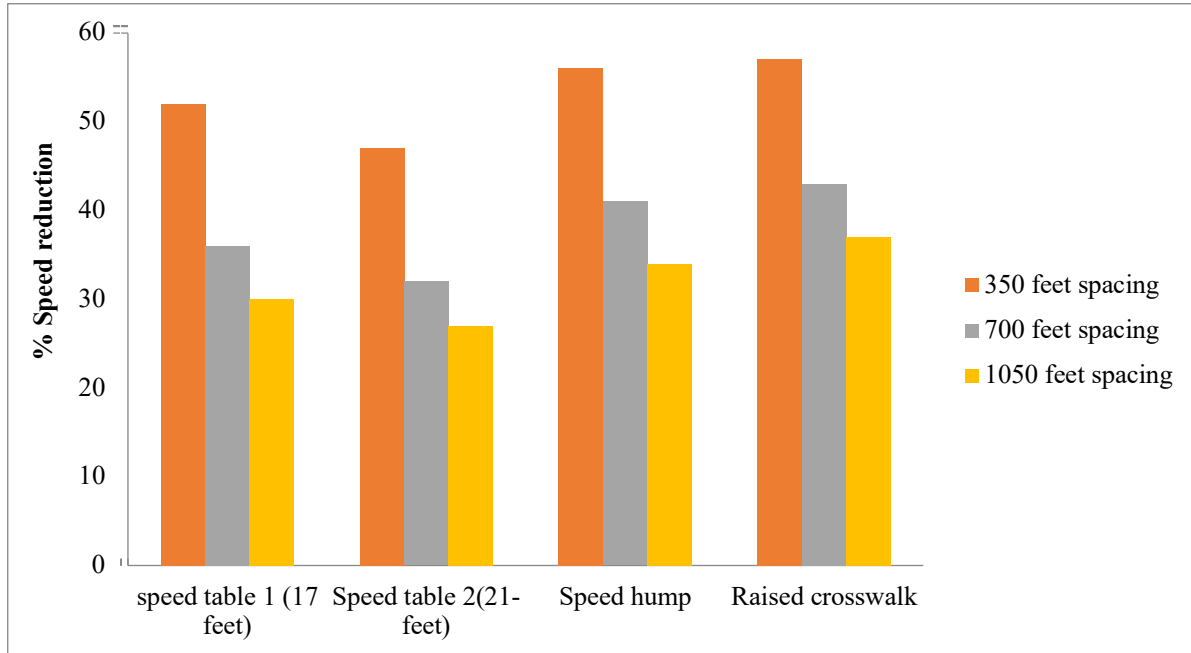
Figure 0.3: Mean Speed reductions due to Traffic Calming

$y = 0.0083x + 12.814$
$R^2 = 0.9234$

$y = 0.009x + 11.153$
$R^2 = 0.9321$

$y = 0.0089x + 10.133$
$R^2 = 0.9446$

$y = 0.0086x + 9.6$
$R^2 = 0.9494$

Figure 0.4: speed spacing model for Traffic Calming

4.2 Capacity Results

Speed-flow relationships were used to estimate capacity of the study segment with presence of various types of calming features. Table 4.1 summarizes the study developed capacity for road segments in presence of various calming features.

Table 0.1: Overall results for capacity for all scenarios

Spacing (ft)	Capacity vphpl			
	Speed Table 1	Speed Table 2	Speed Hump	Raised cross-walk
350	660	690	650	670
700	690	740	680	675
1050	750	775	740	730

4.2.1. Speed Tables

The analysis of capacity impact was conducted based on the width of two speed tables available along the study section; that is 17 ft wide (speed table 1) and 21 ft wide (speed table 2). It was found that the capacity varied with spacing of calming features as well as the number of calming features. Figure 4.5 shows the speed-flow relationships for the 17 ft wide speed table. Figure 15 shows the speed-flow relationship for a 21-ft wide speed table. As shown in Ta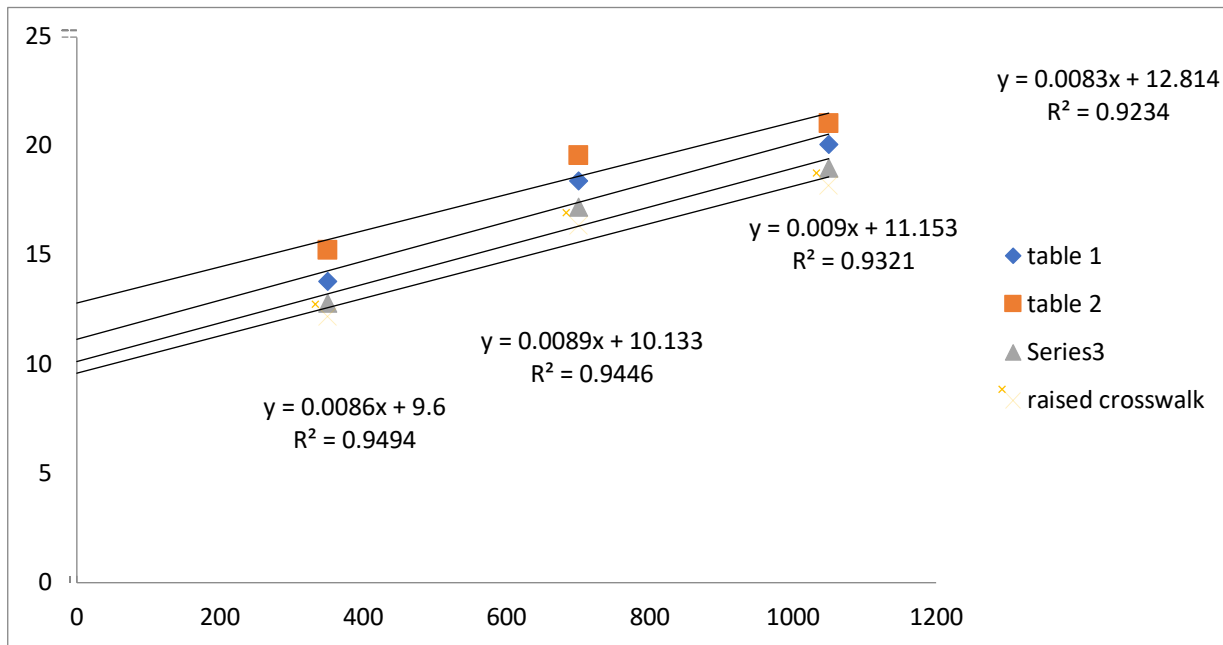ble 4.1, the capacity varied with spacing and number of calming measures implying that the capacity is high for wider speed tables (21 ft) compared to narrow speed tables (17 ft). Spacing narrow speed tables (17 ft) at 1050 ft apart resulted in about 23% reduction in capacity, spacing at 700 ft apart reduce capacity by 29% and spacing of 350 ft reduces by 32%. Wider speed tables (21 ft) resulted with slightly lower reduction in capacity compared to 17-ft wide tables. For instance, spacing 21-ft speed tables at 1050 ft apart resulted in 20% capacity reduction while spacing at 700 ft resulted to 24% capacity reduction. Non-parametric statistical testing found the capacity reductions of 17-ft and 21-ft speed tables are not significant. Further analysis on capacities showed that for each increase in number of calming feature results into linear decrease of capacity by approximately 20, 37 and 34 vehicles per hour per lane when 17 ft speed tables are spaced 350, 700, and 1050 ft apart respectively. For 21-ft speed tables, each unit increase in calming feature results into a linear decrease in capacity for approximately 15, 35, and 27 vehicles per hour per lane when speed tables are spaced 350, 700, and 1050 ft apart respectively.
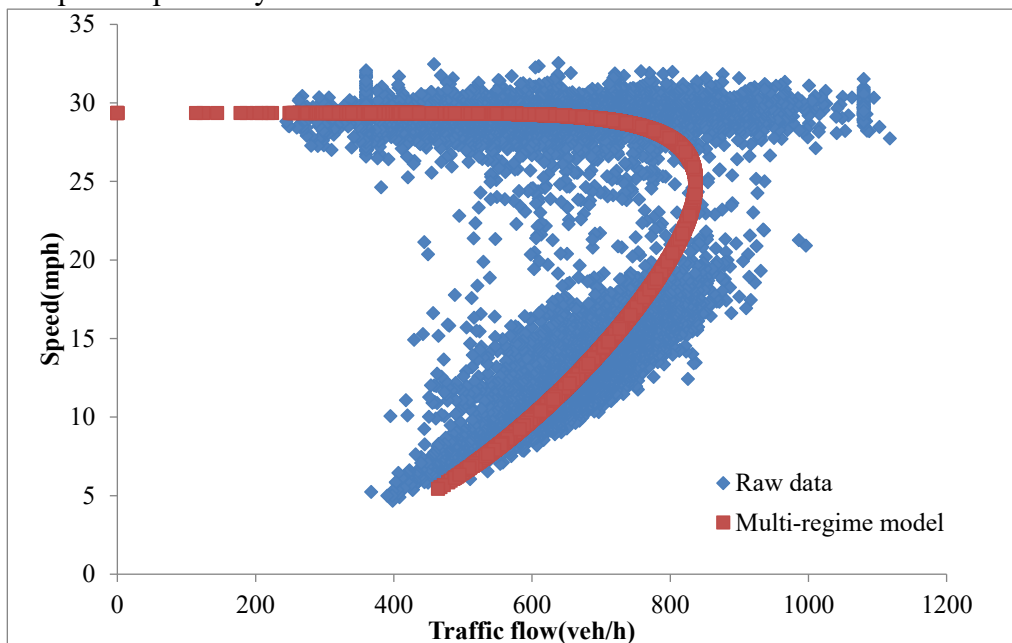
Figure 0.5: Speed table 1 (17-ft table) Speed-Flow Relationship
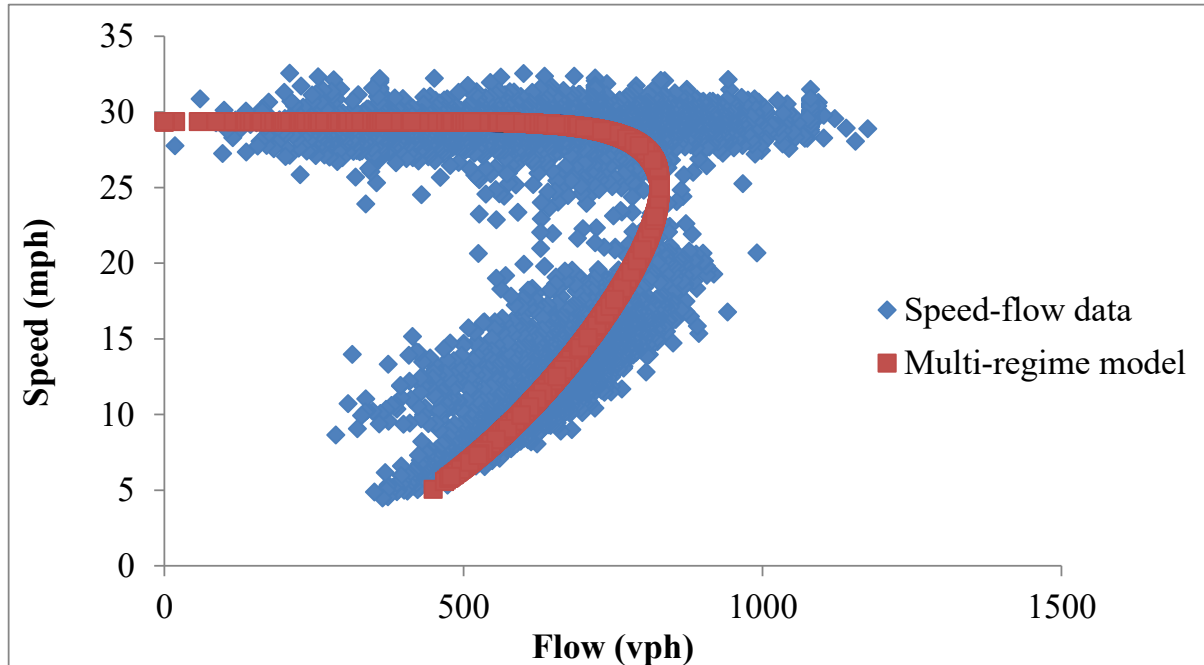
Figure 0.6: Speed table 2 (21-ft table) Speed-Flow Relationship

4.2.2. Speed Humps

The speed-flow relationship for speed humps spaced at 700-ft apart is shown in Figure 4.7. The capacity differed from free-flow capacity in which spacing the features at 350 ft reduced capacity by about 33% while a 700 ft spacing reduced capacity by 30%. For each increase in speed hump results into linear decrease of capacity by approximately 21, 39, and 36 vph when speed humps are spaced at 350-ft, 700-ft, and 1050-ft respectively.

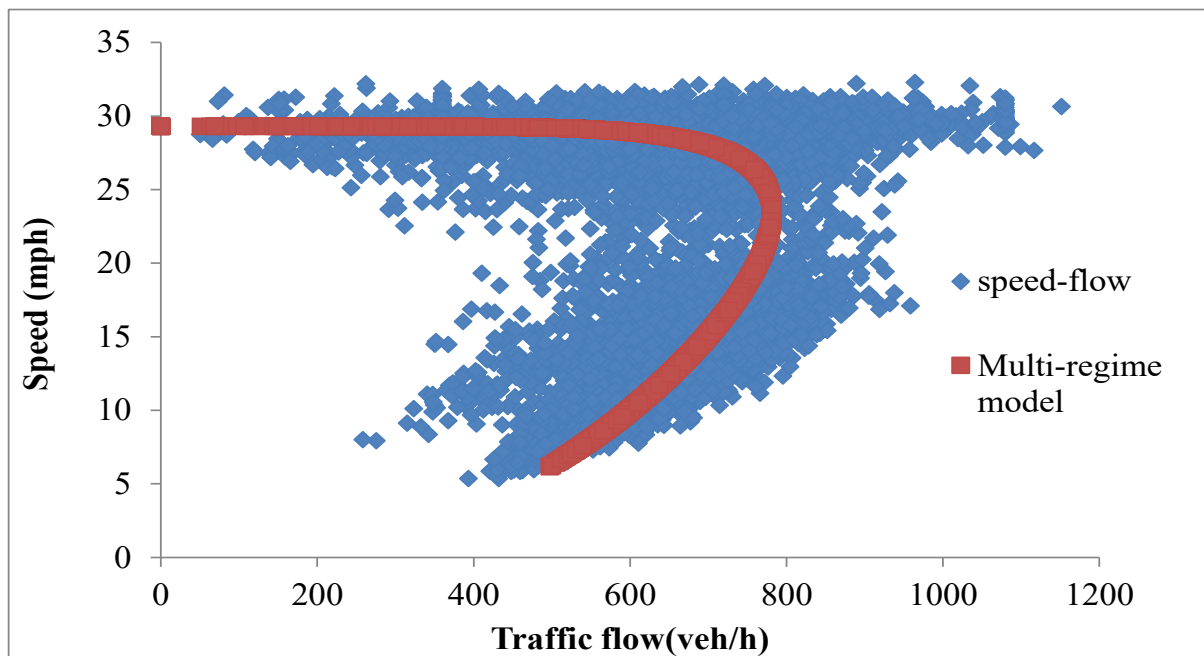**Figure 0.7:** Speed-Flow Relationship for Speed humps spaced at 700 ft apart

4.2.3. Raised Crosswalk

On raised crosswalks, the installation of these features at a spacing of 350 ft caused 30% reduction in capacity. However, the capacity decreased by 25 % when these calming features are spaced at 700 ft. In comparison, when speed tables are spaced at about 350 ft spacing the capacities are reduced by 32% and 33% for speed humps. This shows raised crosswalks reduce capacity less compared to speed tables and speed humps though not significantly.

4.3 Conclusions

Traffic calming measures are installed along roadway segments for the purpose of reducing traffic speeds and/or cut-through volumes, for safety and livability purposes. However, these calming features sometimes lead to reduced capacity that is worthy evaluating. This study used VISSIM microsimulation to simulate the impact of speed calming features and spacing to capacities of residential roadways. GPS collected speed data were collected along the study then simulated through VISSIM to characterize driving behaviors for speed tables (17-ft and 21-ft wide tables), speed humps and a raised crosswalk. About 40 trips were generated using test vehicles equipped with GPS were obtained from drivers who had no idea of the purpose of the study to avoid skewing the driving speeds. The valid numbers of runs were used to develop speed profiles and for further computations of accelerations and decelerations at the approach and exit of the respective calming features. The new approach for estimation of capacity in a road segment with presence of calming measures was developed in this study. The study concluded that there was a minimal difference in capacity resulting from a 17-ft wide speed table compared to 21-ft wide speed table. However, the 17-ft table produced slightly higher reduction in capacity when spaced at 350ft, 700ft and 1050 ft, the speed tables of 17 ft when compared to 21 ft speed tables. The capacity reductions were 30% for 1050 ft spacing, 34% for 700ft and 37% for 350 ft spacing. For all type of calming features evaluated, the addition of number of calming measures in a link resulted into linear decrease in capacity.

Furthermore, from this study, it was found that the traffic calming devices significantly reduce the speeds of vehicles, and it is best to keep spacing of 630 ft or less to achieve desirable crossing speeds of less or equal to 15 mph especially in a street with schools nearby.

The report therefore concludes that speed tables are slightly better than speed humps and raised cross-walks in terms of preserving the roadway capacity. The report also concludes that spacing the speed tables or speed humps or raised cross-walks at 1050-ft instead of 350-ft improve capacity by approximately 13%.

CHAPTER 5: ROAD DIETS

5.1.Introduction

Over the course of the 20th century, four (4) lanes roads became prominent (normal throughout the country). No engineering guidance during that period encouraged consideration of a three-lane alternative. A few years later due to increase in motor vehicles, many roads became congested and hence more lanes were added to increase capacity without careful examination of the pedestrian's safety. Unfortunately, these costly expansions of road infrastructures have not given the desired results [51] [52] [53]. Nowadays, these roads are unsafe and therefore, a solution which tends to improve safety by reducing highway fatalities and serious injuries is needed. One such a solution is the use of road diets. Road diets involve reallocation of road space through reduction of the number of motorized traffic lanes. The freed-up space can be used for the following features: (1) A bike or parking lane which can be used to increase the buffer between vehicles and pedestrians walking along the sidewalks or fixed objects, (2) space for pedestrian refuges, (3) a reversible center lane, and (4) addition or widening of footpaths. These types of public safety treatments can result in a crash reduction, improved livability, and community support. They also encourage walking, bicycling, and transit use [54]. However, these road diets can also result in negative aspects which are worth evaluating. The tradeoffs include: delay, longer queues and travel times, increase of rear-end crashes, increased emissions, and diversion from the corridor. In order, to address the congestion concern due to road diet installment, the traffic signal timing along the corridor may be optimized to improve the progression of traffic and allow easy access of motorists at stop-controlled intersections. This research evaluated the road diet impacts using Microsimulation and Surrogate Safety Measures (SSAM) by assessing the capacity impacts and safety effects of road diet conversions.

Four lanes have quite a few conflict points; these are the major points where a crash can happen. The common crash types experienced in four-lane roads are emerging left turn lanes, sideswipe crashes, and rear end crashes. Road conversions with 3 lane configurations reduce the number of crash points; the middle shared left turn lane smoothly takes left turners out of the traffic flow. This causes improvement in operating efficiency and safety as a result of removing left turning traffic and avoid queue which could form behind such vehicles while at the same time removes lane changing. Further, these conversions can result in lowering of speeds which in turn improves the safety of the segment by lowering traffic crashes and provide longer reaction time [55].

There has been considerable discussion recently on the Road Diet safety analyses. These research studies have featured important factors such as the number of treatment sites, traffic volume, and key safety results. Pawlovich [56] reported 25.2 percent reduction in crash frequency and 18.8 percent reduction rate for 30 sites comprises of 15 roads diets and 15 comparison sites. A similar study was conducted by Li et al [57] in 15 treatment sites throughout Iowa, a road diet was found to reduce all crashes by up to 29% per mile section, and 18.8% reduction in crash rate. Research conducted by Knapp and Giese [58] studied 13 road diet sites from Montana, Minnesota, California, Washington, and Iowa. The authors found that road diet conversions resulted in total crash reductions ranging from 17 to 62 percent [58]. A study evaluating road diets in New Jersey found that the average speeds were reduced between 1 and 9 miles per hour [59]. Li and Tian conducted a road diet case study in Reno, Nevada that found average speeds to be reduced by 2 to 3 miles per hour [60]. Another study was undertaken by Gates in Minnesota found more reduction of 44 percent in the total number of crashes. The study also showed the reductions in both mean

and 85th percentile speeds due to the presence of road diets. The study by Knapp and Giesse specifically cited that 85th percentile speeds reduced by less than 5 miles per hour.

The time and data gathering constraints have led to the use of traffic simulation as an alternative approach to evaluating the operation of road diets. Through traffic simulation models, one can assess changes in road configurations. For example, Noland et al. [61] investigated the feasibility of a road diet by analyzing the results of a micro-simulation of the traffic network using VISSIM software. The key output provided by the model is the total travel time within the network as well as the time each vehicle is delayed. Stamatiadis et al. [62] proposed guidelines focused on evaluating and comparing the operation of three- and four-lane roads at signalized intersections to provide basic guidance as to when the road diet conversion is appropriate. However, the effect of frequent stop and slow-moving vehicles that block lanes of traffic on road diet capacity has received less attention in the research. Knapp et al [63] simulated comparisons of a quarter-mile, four-lane, undivided roadway with a three-lane roadway, each having different percentages of heavy vehicles, one to two bus stops, and various headways and dwell times (with a set amount of entering volumes, number of access points, and turning volumes).The study showed that the impact of these vehicles on average arterial travel speed was much higher along the three-lane cross-section than that of the four-lane undivided roadways. Further, very few studies have sought to use surrogate safety assessment tools with microsimulation to investigate the operation of road diets.

5.2.Objective

The objective of this was to investigate the operational impacts of road diet projects on the number and frequency of stopping and slow-moving vehicles. The primary reason for this increased impact is the inability of other vehicles to legally pass frequently stopping or slow-moving vehicles. The number and duration of vehicle stops along the corridor during the peak hour will be considered. The study also examines the information on the level of safety of road diets using a surrogate measure of safety. The study is implemented using VISSIM microscopic simulation software and SSAM. In a microsimulation environment, car-following and lane-changing rules prevent simulated vehicles from ever crashing. However, safety can be estimated by surrogate measures of safety. FHWA's Surrogate Safety Assessment Model (SSAM) is designed to analyze simulated vehicle trajectories in order to quantify conflicts that are surrogate measures of safety

5.3.Influence Bus Stops Evaluation

Frequent stop and slow-moving vehicles have a greater impact on the operation of a three-lane roadway than a four-lane undivided roadway. Some examples of these types of vehicles are buses, mail, double parked vehicles, buggies, delivery trucks, agriculture, etc. It is very important to take into account the number and duration of vehicle stops along the corridor (at peak times). One major concern with a road diet installation is that stopped buses in the now-singular through lane block all downstream vehicles while boarding and alighting. This blockage of travel lanes causes congestion as traffic backed up behind buses while loading and unloading services at the curb. A similar consequence as a result of mail delivery has been found in urban areas in other studies [64]. Prior to a road diet installation, vehicles were able to able to pass the stopped buses or mail carries using the inside lane. The blockage that occurred after the conversion may result in some vehicles illegal maneuver to pass in the two-way turn lane (TWLTL). In our selected area, there were no bus turnouts. The bus turnouts in the road diets provide a space away from a travel lane for

potential accommodations for bus operations (e.g., stopping, loading, unloading). According to other studies [65] [66], bus stop locations should provide at least 50 feet in length for each bus. However, this is not always the case for most of the road diets. Most transit operators prefer in-lane stops versus turnouts due to the difficulties of through lane ingress from the turn-out. These buses making stops at the travel lanes interfere with the flow of vehicular traffic. The absence or presence of narrower bus pull-offs caused by the presence of sidewalks makes the condition worse. The frequency of stops is another major factor which can attribute the reduction of travel lanes for other vehicles. One possible mitigation measure to minimize the impact of frequently stopping vehicles is to provide pullout areas at specific locations along the corridor. Another possible mitigation is to use some transit lanes. On the other hand, In some cases, road diets were deemed positive by the transit agencies [67] [68].

In order to design an appropriate measure for a smooth flow of traffic, it is very important to study the influence of bus tops on traffic flow. Hence in this study, the extent of speed reduction in the road diet suffered by different vehicles due to the location of curbside stops and bus bays at various roadway and traffic conditions were analyzed. There are three types of bus stops in urban areas which are curbside stops Bus bays, and Bus boarders. The presence of curbside stop creates a temporary bottleneck, reducing the road capacity, during its dwell time. Bus bays are usually utilized for locations on high volume arterial roadways. However, in this study, only the two prior bus stops were used for analysis.

5.4.Conflict Analysis

5.4.1. Surrogate Measures of Safety for Road Diets

In addition to conducting formal safety assessments of Road Diets using data-driven analysis techniques based on pre- and post-installation crash data [55] [60], surrogate measures of safety can provide valuable feedback to State and local agencies regarding both actual and perceived safety outcomes. The limitations of other methods are to wait until a crash occurs, but in reality, there are a lot of near misses. A surrogate measure of safety can provide information on the level of safety of a location or system using the information other than crash data. Surrogate Safety Analysis Model (SSAM) [69] is a method to automate a conflict analysis by directly processing vehicle trajectory data produced by microsimulation models including VISSIM, AIMSUN, Paramics, and TEXAS. The analysis steps (Workflow) involve the following procedures:

- Microsimulation Modelling
- Producing Trajectory (TRL) File by SSAM
- Analyzing Trajectory (TRL) File by SSAM
- Making an inference

In this context evaluating the impacts of access management alternatives of these road diets installed using crash data, is of vital importance. The road diets were already installed and therefore, in a conventional way one would install a new alternative and wait to collect crash data for comparison which is subjected to cost and time issues. Surrogate safety assessment model (SSAM) can reduce cost and time issues, both spatial analysis and filtered analysis of specific locations can be done, and identification of conflicts are defined, meaning less uncertainty for comparison. The traffic conflicts are identified, classified, and evaluated in the vehicle trajectory data output from microscopic traffic simulation models. The trajectories describe the course of vehicle positions through the network. This includes the z coordinates of a vehicle. Figure 5.1

illustrates the conflict angle; an approximate angle of a hypothetical collision between conflicting vehicles based on the estimated heading of each vehicle.

SSAM Measurement Parameters include: (1) Minimum Time-To-Collision (TTC), (2) Minimum Post-Encroachment (PET), (3) Maximum Deceleration rate (MaxD), (4) Maximum Speed (MaxS), (5) Maximum Speed Differential (DeltaS), and (6) Vehicle Velocity Change (Delta V). In the present analysis, time to collision (TTC) as a threshold to establish whether a given vehicle interaction is a conflict and the relative speed (DeltaS) as a proxy for accident severity were used in this research. Their definitions are as follows [70] :

- "TTC" is the minimum time value observed during the interaction of two vehicles on a collision course. If at any time step the TTC drops below a given threshold [1.5 s in this work, as suggested for urban areas [71]], the interaction is tagged a conflict.
- DeltaS is the difference in vehicle speeds as observed at tMinTTC. More precisely, this value is mathematically defined as the magnitude of the difference in vehicle velocities (or trajectories)., such that if v1 and v2 are the velocity vectors of the first and second

vehicles respectively, then DeltaS = || v1 - v2 ||.
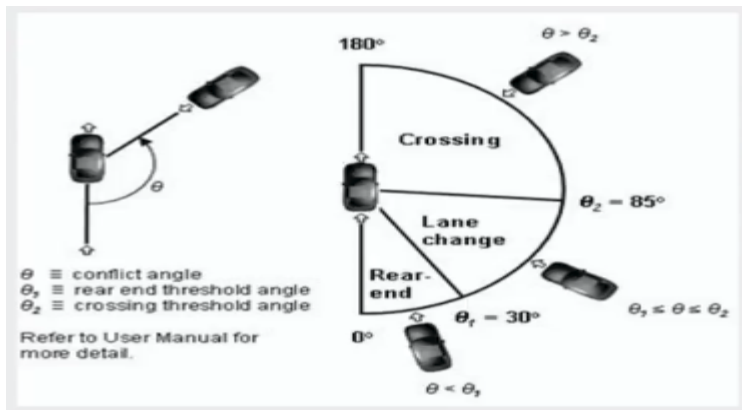
Figure 0.1. Conflict types angle [72]

Surrogate measures give an indication of the risk of crashes. The greater the number of conflicts the greater the number of crashes expected. Validation studies conducted by FHWA [69] suggest that there is a correlation of SSAM conflicts with crash data based on 83 intersections modelled in microsimulation. As equation (1) suggests there is a strong correlation between conflicts and crashes. The number of crashes/ year can be estimated from the model.

$$\text{Crashes/year} = 0.119 * \left(\frac{Confict}{Hour}\right)^{1.419} \tag{1}$$

5.5. Methodology

5.5.1. Microscopic simulation

The road diet in this study was evaluated using VISSIM micro-simulation software. PTV [73] states that the traffic model used in VISSIM is a discrete, stochastic, time step-based model on the microscopic level with driver-vehicle-units as single entities. Due to its flexibility in network structure, it gives the user the confidence to know they can model any type of geometric configuration or unique operation/ driver behavior encountered within the transportation system. VISSIM does not have a direct way to code a shared lane. Therefore, lanes with opposing traffic were coded separately. The model was developed in this study area to reflect the existing

conditions of the 3-lane cross section of the corridor. This model was calibrated based on the available field travel times. Calibration of the model ensures the model reflect the real-world conditions, that is, driving behaviors and geometric characteristics of the roadway. Only AM hours operations were considered for these models.

Vissim has the following advantages compared to other simulation models:

- Powerful lane changing behavior
- Modelling of parallel vehicles flows
- Collection of different vehicle types and user-defined changes in driving behaviors
- Different types of traffic demand modelling
- True multiclass networks (route choice can be determined for each vehicle type

5.5.2. *Study Site*

Microscopic simulation was conducted for a road diet located in the city of Nashville, Tennessee (Figure 5.2). The 51st Avenue complete street in the Nations Nashville makes the neighborhoods more livable. This was a fast-changing neighborhood, and hence the street was made to work better for drivers, bicyclists, and pedestrians alike without adding time to their commutes. The four lanes were transformed into a complete street to enhance and create a sense of place for the growing neighborhood. The street is composed of the two-way turning lane, on-street parking, slower speed limits, and dedicated bike lanes. The 51st Avenue North traffic calming segment starts from Charlotte Avenue to Centennial Boulevard. The corridor is in the neighborhood that is situated in the north of Charlotte Pk and Interstate 40 on the west side of Nashville. The original street had four traffic lanes, two in each direction. The road diet allowed for the re-purposing of the existing pavement to provide on the street and a two-way cycle track from Alabama Avenue to Centennial Boulevard. The two-way cycle track, signified throughout the corridor with green pavement and specialty bike pavement markings, uses flexible bollards and delineators to provide physical separation from the adjacent traffic. Pedestrian infrastructure was upgraded with the addition of decorative crosswalks and signage to provide increased visibility.

Figure 0.2. The layout of the Test Site

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There is only one main transit route operating along 51st Ave Street. Headways, or the time between buses, were ranging from 30 minutes to 20 minutes during peak times. Most of the bus stops along 51st Ave N include a sign pole with no shelters or seating. Bus stops at Tennessee Ave, Illinois Ave NB, Georgia Ave NB, and Charlotte Ave.

5.5.3. *Data Input*

For the purpose of calibration and analysis, traffic and GPS data were collected. Traffic data include intersection turning movement counts, turning ratio at an intersection, daily traffic volumes by direction, the signal timing of the signalized intersection, the schedule of the transit operation, the transit dwelling time at each bus stop and dimensions of stops, and operating speed information. The Miovision Scout unit [44] was used to measure traffic flow at major intersections along the study corridor. The Miovision Scout unit uses video to collect traffic movements and roadway volumes in intersections and roadways. This camera system was mounted on a stand with its top camera directed toward one direction of traffic, fixed at sidewalk rails, looking down on traffic. The camera was set up to record vehicles in all lanes and intersections. Data were collected for 12 hours period during weekdays between 7 am and 6 pm. Data were extracted and screened for analysis and VISSIM simulation.

For the signal plan; in the existing case, there are four signalized intersections out of 10 along the whole corridor, which are Charlotte Ave & 51st Ave, Alabama & 51st Ave, Delaware & 51st Ave, and Centennial &51st Ave. All four signalized intersections are fully actuated, with a detection zone located at the stop line, and the detectors are operating in the "presence" mode. The existing plans signal plans at Alabama & 51st Ave N and Delaware & 51st Ave North have two phases with ring barrier controller structure. They have cycle lengths of 70s seconds at AM peak time and 65 seconds at PM peak time. The two intersections are running on signal procession due to the short distance between them. Table 5.1 shows the traffic volume and signals timing settings for Delaware &51st Ave N.

Table 0.1: Traffic Volumes & Signal Timing Settings

Traffic volume											
Phase Number	1	2		3	4		5	6		7	8	
Lane Type	SBL	NBT	NBR	WBL	EBT	EBR	NBL	SBT	SBR	EBL	WBT	WBR
Volume (*veh/hr*)	4	242	10	45	3	10	3	5	320	1	45	135
Signal Timing Setting											
Min Green		10			7			10			7	
Veh Extension		3			3			3			3	
Max 1		50			30			50			30	
Yellow		4.0			3.5			4			3.5	
Red Clearance		2.5			2.5			2.5			2.5	

5.5.4. GPS Trajectory Data

A portable Wide Area Augmentation System (WAAS/EGMPS) enabled USB GPS Receiver was used to collect second-by-second vehicle trajectories along the road segment [45] . The GPS provides positional horizontal accuracy up to 5 meters 3D RMS, velocity accuracy of 0.1m/sec and time accuracy of 1 microsecond synchronized to GPS time. Fig. 5.4 illustrates a diagram of speed profiles provided by a GPS receiver along the study segment. Instantaneous GPS speed data for the buses and cars were collected using GPS equipped on the test Transit vehicle or car. The vehicle equipped with GPS is driven along the test route in a similar way to the floating car method. In this study, both the speeds of transit vehicle and car were collected. Five repeated cycle runs of the test were conducted along the same route.

5.5.5. Geometric Design

The process of modeling a road diet in VISSIM starts by tracing an aerial photo of the corridor, specifying each approach number, width, and length of lanes. Once the geometry of the road diet is defined, traffic flows (i.e., vehicles per hour) for each approach are allocated for all directions. The road geometry data were derived from the default map service provided in Vissim. The map was used as the base map for developing the model for simulation. The map provides road geometry data, such as the edges of the road, the centerline of the roads and other geometry. See figure 5.3. In existing case, the section of 51st Ave N in the corridor is bi-directional with a single travel lane on both directions with a two-way left-turn lane in the middle, as shown in Fig. It also features a protected two- way cycle track (bike lanes), slower speed limits, and on-street parking. The portion of the design stretches from Alabama Ave to Centennial Blvd. with the traditional lanes stretching from Alabama Ave to Richland Creek Greenway. There are 6 intersections along the street from Centennial to Charlotte
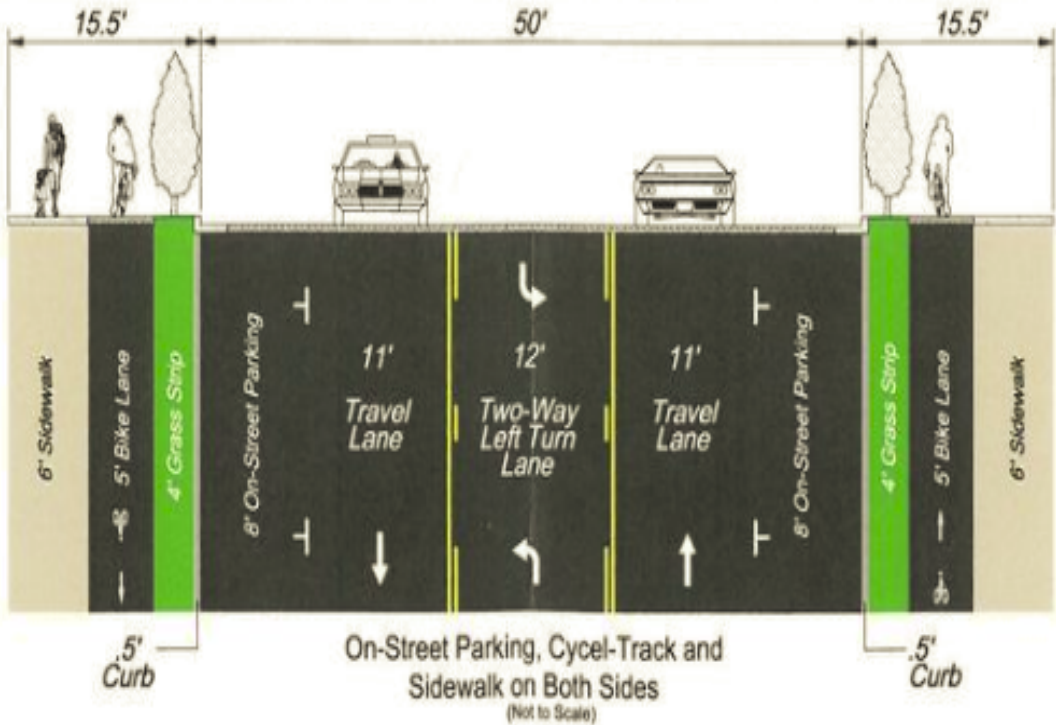

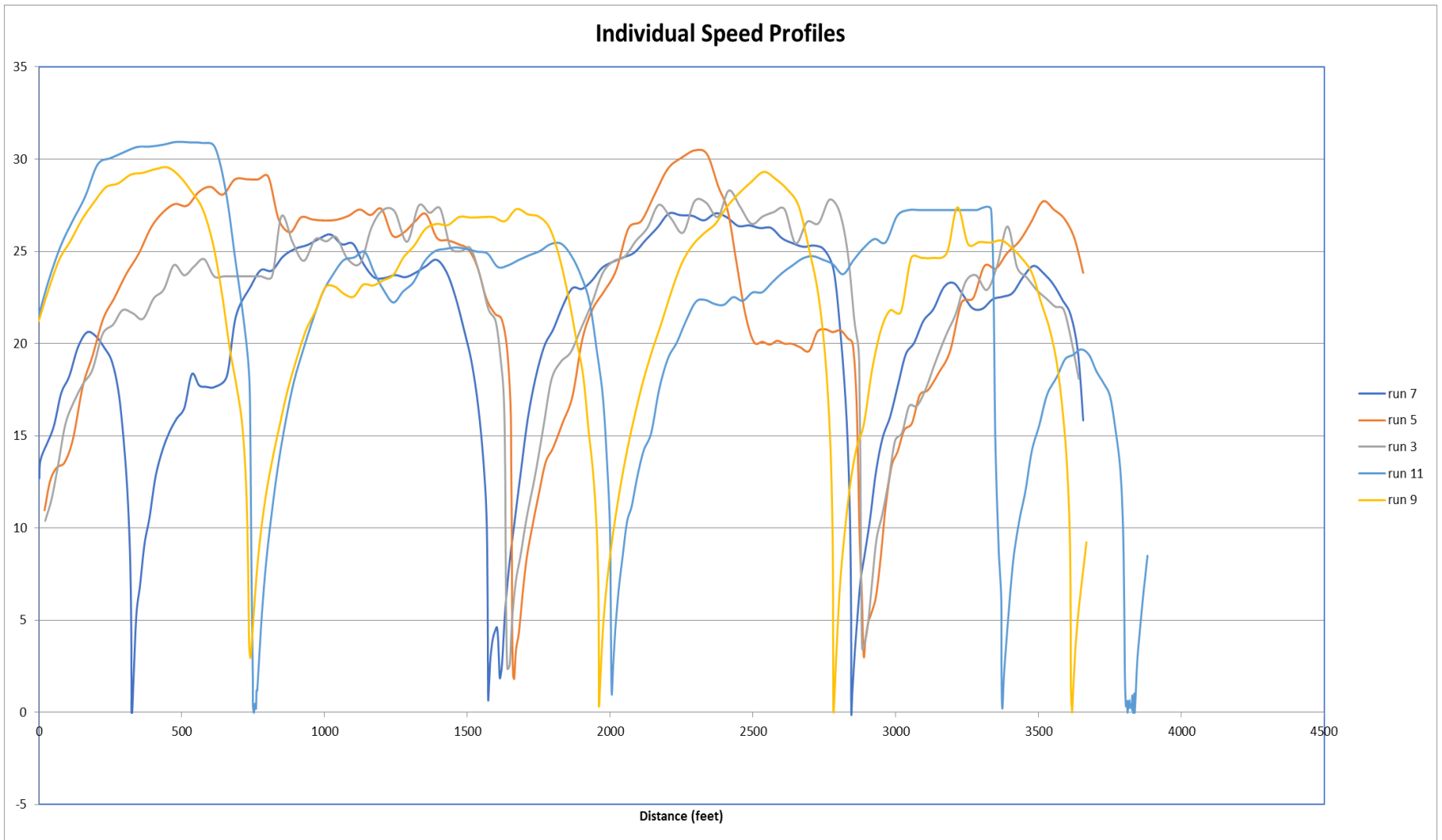**Figure 0.3. Section of the road diet**

Figure 0.4. Speed profiles along the study segment recorded by the test vehicles

5.5.6. Origin-Destination Matrices

Dynamic origin matrix demand estimation was used to estimate the unknown demand values for all O-D pairs with the use of time-varying link flow observations. The O/D matrix was deduced from the collected data sample of traffic volumes. Due to the lack of data, the calibration of the model was made in a qualitative way, based on local observations, known dynamics of the area and used for quality control purposes the traffic volumes recorded in the studied intersections. Each OD matrix in VISSIM applies to a specific vehicle composition. Since the corridor consists of mainly two traffic compositions (cars and buses), each O-D matrix produced two VISSIM O-D matrices, for a total of 10 matrices (15 minutes interval-each with dimensions 12 by 12).

5.5.7. Dynamic Assignment

Vissim supports two forms of input for traffic demands [73]. Dynamic assignment module was chosen to be used. The dynamic assignment automatically determines inlet flows and routing information based on a user-supplied O-D matrix. The routes, or traffic assignments, are generated by the dynamic assignment module by assigning a cost to every route available to each O-D pair and then choosing the route with the minimum cost. For a large network, it is often very difficult and time-consuming to manually define all the route choices from origin to the destination because the route choice of drivers depends on signal control and traffic conditions. It is therefore imperative to model how drivers will choose from a set of possible routes based on a time-dependent origin-destination demand. Dynamic assignment in VISSIM is based on a repetitive simulation, and drivers are made to make their route decisions based on the travel cost they experienced in the previous simulation [74]. The iterative process is repeated until convergence is reached. In this study, firstly, nodes were defined for all intersection and network boundaries making sure that the attribute "use for dynamic assignment" is checked. Zones, as specified in the OD matrix, were defined and parking lots were defined at network boundaries of every link in the network. Estimated Origin-Destination Matrix was coded, and the parameters defined based on vehicle compositions and class.

5.5.8. Modeling Road Diet

The road diet was configured in VISSIM by realigning the lanes for vehicular traffic to fit within a narrower right of way that would allow for the installation of bicycle lanes on both sides of 51st Avenue North. Since VISSIM does not have a straightforward way to model a shared left turn lane, the lane alignment at each intersection has been carefully constructed so that left turning vehicles from 51st Avenue North and from the side streets interact in a realistic way. Two links with overlapping lanes running in opposite directions were developed. Then the priority rules and the lane change distances were assigned to the left turn connectors. The priority rules kept vehicles from driving through each other in opposite directions and the lane change distance settings kept vehicles from getting stuck and from excessive lane-change crash events (drivers choose and begin to seek desired destination lanes as they entered the network). The simulated network with the road diet was well configured to recreate the vehicular interactions that would result from a shared left turn lane and, most importantly, to exhibit the expected capacity for vehicular traffic in the corridor.

Morning peak times were used for this study. The next step was to encode the signal control parameters. The NEMA (the National Electrical Manufacturers Association) style controller model included with VISSIM was used for all intersections in this study. Detector locations were defined for intersections with full actuated control strategies. The information on detector locations and

phase assignment were available from the signal intersections files which were provided by the Metropolitan Government of Nashville and Davidson County [75]. However, the information on the lengths of detectors was not available, and therefore, the detectors were assumed to have a length of 30ft and were placed 32.679ft from before the stop line. For all the intersections, the priority rules were implemented for all the permissive left turns and the reduced speed areas were added for turning movements. A priority rule is defined through three parameters: minimum gap size, minimum headway, and maximum speed. The minimum headway of the priority rule was calibrated to mimic the performance of the crossing vehicles in the presence of slow-moving or queuing traffic on the main road. The default parameter suggested by PTV VISSIM for this parameter is 16.4 ft. For all intersections in this study, the minimum headway was changed to 200ft.

In the reduced speed areas, each vehicle made maintained near constant speed. The location, speed distribution, and deceleration rate of reduced speed areas have been determined using field observation. Next speed profiles, vehicle-type characteristics, and traffic composition configured for each intersection and the corridor. The traffic composition was mainly composed of cars, heavy good vehicles, and buses. The percentage of cars and other vehicles (HGV and buses) observed in the peak hour were 92% and 8% respectively. The desired speed profile was found using test vehicles to range from 30mph to 30mph, 35 mph (85th percentile speed).

Microsimulation models were utilized to compare the operational and safety performance of the road diet (3-lane section) due to the presence of the stopped transit. Different volume scenarios were developed. The technique was to convert crash models were expressed in units of ADT to traffic volumes in the simulation are expressed in the unit of veh/hr. ADT was converted to Hourly Volume (HV) by using the K factor as can be seen in equation 2.

$$ADT = \frac{HV}{K} \qquad (2)$$

Where:

ADT   is the average daily traffic volume

HV   is the hourly volume

K   is the conversion factor

The value of K varies with the area type. For this research, the value of K of 0.093 for the urban area was used as recommended in the Highway Safety Manual [33].

The study segment was modelled in VISSIM and tested for realistic vehicle behaviors. After running the VISSIM model several times with different random seeds for the period of 3900s (including 300s warm-up period), the TRJ files were imported into SSAM application to identify traffic conflicts and the corresponding surrogate safety measures. SSAM was configured to use its default values conflict identification thresholds. Namely, the (default) TTC and PET values used were 1.5 seconds (1.5s in this research, as suggested for urban areas [71]) and 5.0 seconds, respectively.

5.5.9. Modelling Transit Operations

Transit vehicles modelling was conducted based on empirical observations from the site. The effect of blockage lanes due to stopped transit vehicles were observed in the field observations and microsimulation confirms the relationship between the location of the blockage and the effect on capacity and delay. Live video feeds collected from the site in Nashville for these complete streets were used to observe the operation of the bus. The videos were recorded from the camera mounted at different locations along the corridor for the duration of at least six hours in several consecutive days. Following are a number of qualitative observations made on the transit vehicles operating on road diets: (1) Transit buses stopping for passengers at stops which are distributed along the length of the corridor, and (2) The blocked travel lane has different effects on traffic moving; some drivers wait behind the buses while others merge into the shared lane to get around the transit vehicles before returning to the desired lane.

Transit vehicles operating on road diets have a negative impact on traffic safety as previously elaborated; the magnitude has not been systematically quantified. A large number of conflicts were observed in the model as the number of cars queued up behind the stopped buses waiting to perform a passing maneuver increased. These conflicts were recorded by SSAM as either rear end or lane-changing maneuvers. The increase of rear-end conflicts increased due to vehicle stops, this increase in simulated crashes was due to queued cars changing lanes abruptly. The diagram (Figure 5.5) attached indicates the screenshot of the simulation animation, in which from the visual inspection of the lane changing behavior, a trailing vehicle (highlighted in the green box) drives through a transit bus that was stopped in designated bus stops through a lane-change. The similar situation may occur for the case of vehicles stopped on a red light with other vehicles approaching. One vehicle may fail to recognize the presence of another vehicle and partially passes through it. SSAM also considers this event as a crash.

Simulations were run for a baseline case of road diet in which no blockages occurred. Then, a series of simulations were run to evaluate the effect of a blocked lane associated with a stopped bus vehicle at distances from 0 to 175 feet from the intersection stop line. 10 replications were conducted for a base case condition with no blockage and then for cases in which a transit bus stopped at 0, 25, 50, 75, 100, 125, 150, and 175 feet from the intersection stop bar. Fitzpatrick [76] also considered different alternatives for locations include near-side, far-side, or midblock locations, and curbside or bus bay designs

As the effect of a bus stop on other vehicular traffic depends on bus dwell time, dwell times of 10s, 20s, and 30s were assumed while comparing the model for different flows [77]. For each of the dwell times considered, traffic flow was increased in steps until the capacity flow of the road diet approach was obtained. Assume all buses in the stream stopping at the stop. The effects of bus dwell times at a bus bay/curbside stop alternative were also evaluated.
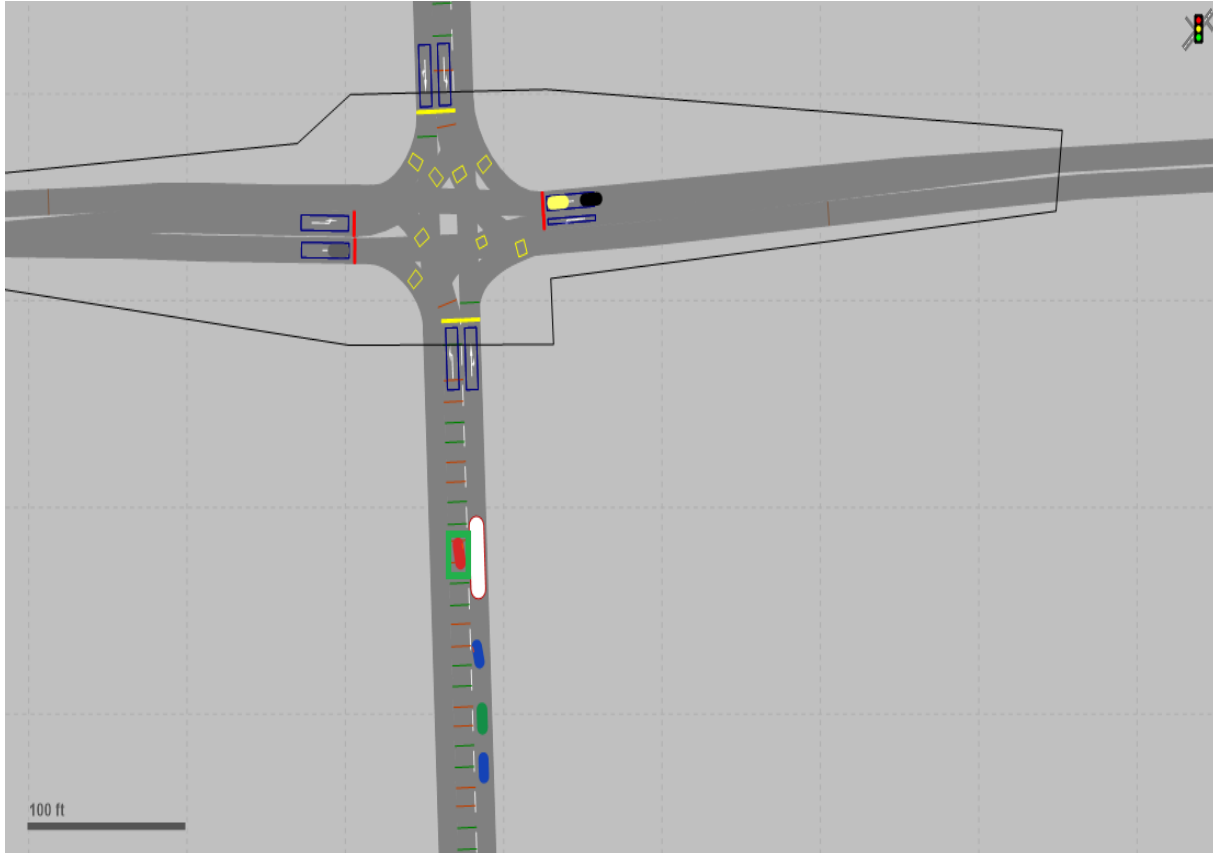
Figure 0.5. Transit Operations on a road diet

5.5.10. Model Calibration and Validation

In order to produce a microsimulation model faithful to traffic conditions observed on the road diet, traffic patterns and driver behavior were replicated using VISSIM microsimulation software. Driver behavior in VISSIM is composed of a car following, lane change, lateral and signal behavior model. The following were parameters were considered for the calibration: traffic assignment (OD), speed distribution (Average speed of cars, average speed of trucks , and average speed of buses), reduced speed area, conflict areas parameters, and driver behavior elements. Also, the speed of all vehicles crossing the curbside bus stop, dwell time distribution (mean, S.D) were measured in the model and matched the field values. After the calibration of the model, the model was validated. The first step of validation is visualization [78], checking the operation of vehicles in road diets and bus movements and comparing to the field. Then, the model was again validated using travel times collected on different weekdays using test vehicles equipped with GPS. It was noticed that the average difference in travel times in the VISSIM model from the field was below 15% indicating a reasonable matching between the simulated and observed travel times. Generally, all validation results for the two directions (NB and SB) were satisfactory with minimal errors. It was concluded that the model was well calibrated and validated.

5.6.Evaluation

5.6.1. *Lane Changing Evaluation*

Lane changing refers to the process where a vehicle traverses to an adjacent lane from its present lane. Lane changing is a significant parameter when modelling driver behavior using microscopic traffic simulation [79]. Ramanajam [80] categorized lane changes into two (2) main groups based on what triggers the process including Mandatory lane Changes (Necessary lane changes) and Discretionary Lane Changes (Free lane change). Mandatory Lane Changes (MLC), which constitutes of lane changes that are imposed by a lane drop, incident or because the vehicle is approaching the exit of a junction while Discretionary Lane Changes (DLC) describes lane changes that are performed due to a driver's desire of traveling by higher speed or with more space. The DLC model is described by Mathew as a three-step process initiated with the decision whether to consider a lane change or nor. Subsequently, the vehicle must check if the desired lane change is feasible, and lastly perform a gap acceptance control.

These lane changing behaviors are implemented in Vissim software. There are two car-following models available in VISSIM: Wiedemann 74 and Wiedemann 99. The lane changing behavior in Vissim is based on a model developed by Willman, 1978 [73]. In order to model lane changing decision in Vissim, Gao [81], as well as Fellendorf [82], argues that the following set of hierarchical questions have to be evaluated: (1) Does the driver desire to change lane? (2) Are the driving conditions improved by a change to the adjacent lane? (3) Is it feasible to safely perform the desired lane change? The lane changes in Vissim depend on the distance to the emergency stop position of the next connector route. PTV AG [81] points out that no matter which type of lane change that is being performed, the initial step when a vehicle wishes to change lane in VISSIM is to find a "suitable time gap" (headway) in the destination flow. The size of this time gap depends on the speed of the own vehicle and the trailing vehicle in the targeted lane. The full set parameters for modeling lane changing behavior in Vissim were studied and adjusted.

To reduce the effect of unusual lane-changing behavior, the length of each approach to the intersection were extended to give more time for vehicles to decide their downstream paths. Also, driver behavior parameters were adjusted to allow additional time for the minimum lateral clearance. 0.5 seconds was added for the minimal lateral clearance. The essence of this adjustment is to reduce simulated crashes resulting from lane changes.

5.6.2. *Safety evaluation*

Surrogate safety evaluation is a widely accepted alternative to crash data analysis for engineering applications [83]. Following the randomness and rareness of crash occurrence, statistics can be applied to relate surrogate safety measures with frequency and severity of crashes even before the occurrence of the crashes. Traffic conflict is the commonly used surrogate safety measure which is defined as a situation where two or more vehicles will collide if their movements remain unchanged. A number of conflicts that occur, type and severity of the conflicts can be used as an indicator of traffic safety [84]. In this study, only rear-end and angle conflicts were analyzed because they are the most prevalent at road diets and can be caused by hard-braking and abrupt changing of lanes at the middle-shared lane by queued cars due to bus blockage at the stops. According to the data collected from the Tennessee E-TRIMS database [85] of the road diet installed, 38 % of crashes resulted were angle crashes while 21% came from rear-end crashes.

Specific thresholds are applied to measurable traffic indicators such as time to collision (TTC) and post-encroachment time (PET) in order to obtain working definitions of traffic conflicts. The

Surrogate Safety Assessment Model (SSAM), a Federal Highway Administration software, enables identification of the traffic conflicts by statistical analysis of the vehicle trajectory file which is generated from microscopic simulations. SSAM provides a number of indicators of conflicts based on the trajectory files obtained from the scenario run by microscopic simulation software. In this study, the results from SSAM proved to be useful due to several reasons. The study specifically focused on the safety evaluation of vehicles that are coming to a stop behind the stopped buses on travel lanes. SSAM provided a vast amount of conflict data that was filtered to obtain data that was required for this study. Traffic conflicts occur at different locations due to several different reasons.

VISSIM traffic flow model is a stochastic, time step based, microscopic model that treats driver-vehicle units as basic entities. It uses Wiedemann's traffic flow model which is based on the assumption that there are basically four different driving states for a driver namely free driving, approaching, following and braking [73]. The braking state occurs when a driver applies medium to high deceleration rates if the distance to the preceding vehicle falls below the desired safety distance. This happens if the driver of the preceding vehicle abruptly changes his speed or the driver of a third vehicle changes lane to squeeze in between two vehicles. Further, VISSIM provides a number of interaction states which can be used to check the driving states of the vehicles in the network. Closeup state describes vehicles closing up to a stationary vehicle in front or hindrance, for example, signal heads, stop sign, priority rule, and conflict area. Since the study was conducted on a bus stops at designated distances from the signalized intersection approach of a road diet, the close-up state only could result only on a stationary transit vehicle in front or hindrance due to signal heads.

Location with many conflicts exceeding the thresholds for TTC, PET, and DR and are of high severity of DeltaS and MaxS were studied for the safety implications. For the low values of DeltaS and MaxS, the accidents are classified as Property Damage only (PDO). In this study, locations with conflicts that resulted in high resulting potential severity were highly favored regardless of the number of conflicts. After having the SSAM conflicts, debugging of the results is of crucial importance. Overlapping vehicles in TRJ output identified as conflicts with TTC=0 (crashes) were removed before statistical calculations were performed. These are virtual crashes where the logic in the simulation model does not accurately and completely represent the physical possibility of a particular maneuver

5.7. Results And Discussion
5.7.1. *Influence of Bus Stops*
The results of the simulation of traffic at curbside stops on an 11ft wide road are shown in Fig. 5.6. The figure shows the average traffic speed near the bus stop, for various bus dwell times. It can be seen that up to a traffic flow level of about 600 vehicles per hour, the effects of dwell times of 10, 20, and 30 s duration, are nearly the same. Comparisons of the effects of bus dwell times at curbside stop for non-stop transit vehicle, at various flow levels on an 11ft wide road lane of a road diet, can be depicted in Fig. 5. By referring to the same figure, it can be seen that the presence of bus for 10, 20 and 30 s dwell times have almost 9.5%, 12%, and 20% effect on traffic speed reductions when 300 veh/hr flow is considered. Fig. 5.7 shows a comparison of reduction in speed of traffic on an 11ft wide road lane of a road diet due to curbside stops and bus bays for a mean of 30s with a standard deviation of 5 s dwell time case. It can be seen that a bus bay stop with the

stated bus dwell time, causes an approximate 8% speed reduction to traffic at a flow level of about 1400 vph.
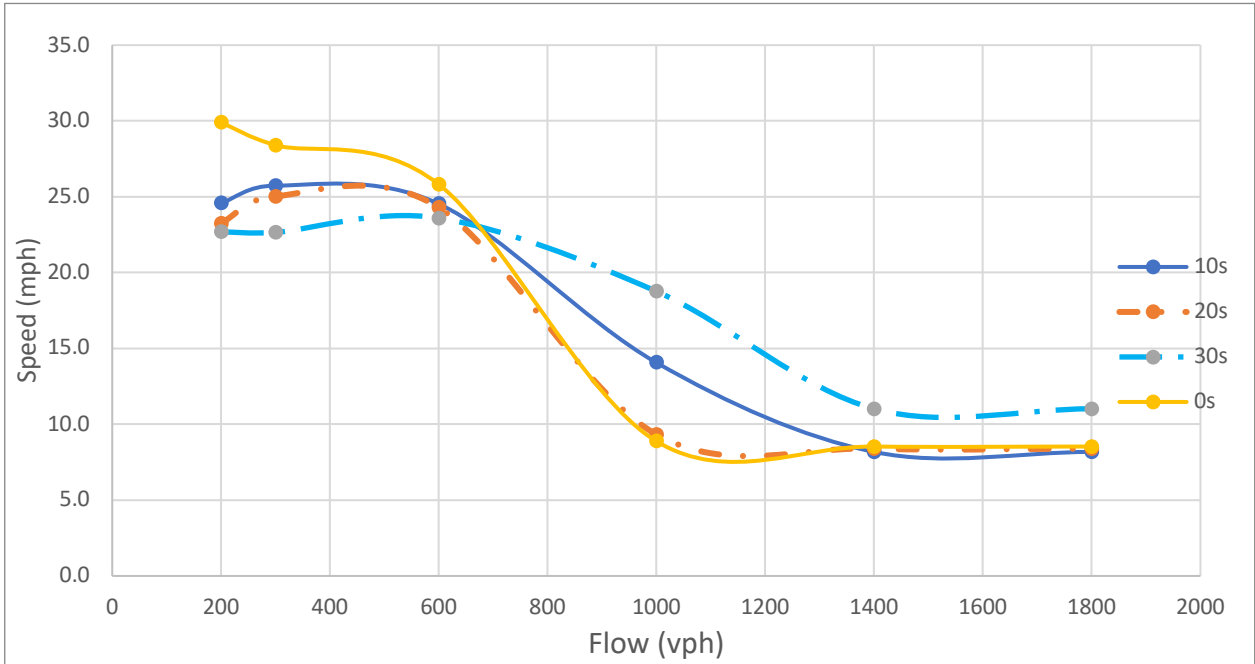
Figure 0.6. Effect of bus dwell time at a bus bay on 11ft wide road of a road diet
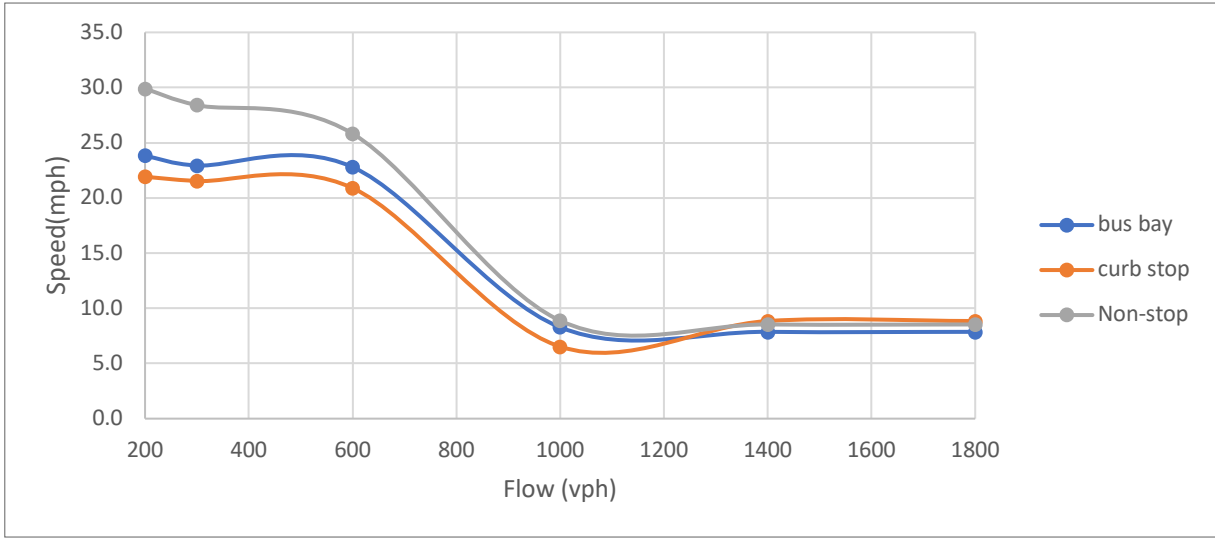

Figure 0.7. Effect of bus dwell time at a bus bay on 11ft wide road of a road diet

5.7.2. *Effect of Transit vehicle on Traffic Safety of the road diet*

There are two notable conflict types associated with transit vehicle on road diets: rear-end conflicts, which can be the result of vehicles traveling in the inside through lane behind a stopping

or stopped left-turning vehicle. Therefore, a vehicle must brake in order to avoid hitting another vehicle from behind; Crossing conflicts occur during lane-change maneuver which poses a risk of collision between two vehicles. An analysis of the trajectories from bust stop locations at 0, 25, 50, 75, 100, 125, 150, and 175 feet from the intersection shows how the number of conflicts is affected by the presence and location of a curbside stop on the link of a road diet. Figure 5.8 shows that the number of rear-end conflicts is significantly greater when the bus stop is at the intersection. The conflicts keep decreasing as the blockage moves away from the intersection until there is no statistically significant difference at approximately 100 feet from the intersection. This distance corresponds to the length of the queue. When the blockage does not interact with the queue of vehicles at the intersection, there appears to be no significant increase in rear-end conflicts. This analysis implies that rear-end crashes are more likely only when transit vehicles stop near the intersection. The same simulation cases were also analyzed for crossing conflicts. Since the operation of a bus blocks a lane of traffic on a road diet, any vehicles traveling in that lane attempts to illegally maneuver in order to proceed along the route. The relationship between the number of crossing conflicts and the location of the curb stop location is shown in Figure 5.9. Repeatedly, there are more conflicts the closer the curb stop is to the intersection on a road diet. In this case, the conflicts decrease linearly with distance until about 100 feet. When the bus curbside stop location is near the intersection, the lane changes from behind the transit vehicle interact more with the vehicles attempt to make left turns to the access points using the shared lane.

Figure 0.8. Effect of a bus curb stop location on the number of rear-end conflicts

Figure 0.9. Effects of a bus curb stop location on the number of crossing conflicts

5.8. Conclusions

Road diets can decrease lane crossing distance and reduce vehicle speeds through converting an existing four-lane, undivided highway to two through lanes and a center, two-way left turn lane (TWLTL). This design allows left-turning vehicles to exit the traffic stream while waiting for a gap to complete their turn and frees up space that can be relocated to other uses. One of the uses is for transit lanes. Although it is commonly noted in the literature that transit vehicles on a road diet have a negative impact on traffic safety and operation, the magnitude has not been systematically quantified. These buses or freight vehicles dwelling at loading areas near the intersection of a road diet temporarily block car traffic to provide bus priority. For the purpose of estimating effective traffic management strategies at critical locations on a road diet, the effects of these obstructions were recognized or accounted for in this study. In this study, a microscopic simulation model developed to replicate the driving behavior of traffic on urban road diets roads has been used to analyze the influence of bus stops on traffic flow and safety. The impacts of safety were assessed using surrogate measures of safety (SSAM).

The results indicate that presence of a bus stops for 10, 20 and 30 s dwell times have almost 9.5%, 12%, and 20% effect on traffic speed reductions when 300 veh/hr flow is considered. Also, up to the traffic flow level of about 600 vehicles per hour, the effects of dwell times of 10, 20, and 30 s duration, are nearly the same. Additionally, a comparison of reduction in speed of traffic on an 11ft wide road lane of a road diet due to curbside stops and bus bays for a mean of 30 s with a standard deviation of 5 s dwell time case was conducted. Results show that a bus bay stop with the stated bus dwell time causes an approximate 8% speed reduction to traffic at a flow level of about 1400 vph.

For safety analysis, an analysis of the trajectories from bust stop locations at 0, 25, 50, 75, 100, 125, 150, and 175 feet from the intersection shows how the number of conflicts is affected by the presence and location of a curbside stop on the link of a road diet. the number of rear-end conflicts is significantly greater when the bus stop is at the intersection. The conflicts appear to as the blockage moves away from the intersection until there was no statistically significant difference at approximately 100 feet from the intersection. For crossing conflicts, again, there were more conflicts the closer the curb stop is to the intersection on a road diet. In this case, the conflicts decrease linearly with distance until about 100 feet.

REFERENCE

[1] PRIMAVERA, "Review of Current Traffic Calming Techniques," 17 November 1992.

[2] ITE/FHWA, "State of the Practice," FHWA, 1999.

[3] A. O'Brien, "Traffic Calming- Ideas Into Practice," *ITE Publication,* p. p37, 1993.

[4] A. . Książek, "Approach to Simulation Assessment of Area-wide Traffic Calming in the Context of Sustainable Development," , 2015. [Online]. Available: http://witpress.com/secure/elibrary/papers/ut15/ut15015fu1.pdf. [Accessed 1 10 2017].

[5] FHWA, "Engineering Countermeasures for Reducing Speeds - Safety | Federal Highway Administration," May 2009. [Online]. Available: https://safety.fhwa.dot.gov/speedmgt/ref_mats/eng_count/. [Accessed 17 9 2018].

[6] F. H. Adminstration, "Traffic Calming ePrimer – Module 8," 13 February 2017. [Online]. Available: https://safety.fhwa.dot.gov/speedmgt/ePrimer_modules/module8.cfm. [Accessed 17 9 2018].

[7] Metro Public Works & RPM Transportation Consultants, "Hillwood Neighborhood Traffic Calming Project," Nashville, 2012.

[8] A. E. Aburahmah and R. A. Assar, "EVALUATION OF NEIGHBORHOOD TRAFFIC CALMING TECHNIQUES IN RESIDENTIAL AREAS," , 1998. [Online]. Available: https://trid.trb.org/view/675843. [Accessed 1 10 2017].

[9] G. . Lee, S. . Joo, C. . Oh and K. . Choi, "An evaluation framework for traffic calming measures in residential areas," *Transportation Research Part D-transport and Environment,* vol. 25, no. 0, pp. 68-76, 2013.

[10] E. R. Petersen, "The effectiveness of low-cost traffic calming applications appropriate for main streets through rural communities," , 2006. [Online]. Available: http://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=2393&context=rtd. [Accessed 1 10 2017].

[11] J. N. Y. Wei, S. T. Ho and C. S. Palanisamy, "An assessment on the effectiveness of traffic calming markings and alternative for speed regulating strips," , 2013. [Online]. Available: http://diva-portal.org/smash/get/diva2:759733/fulltext01. [Accessed 1 10 2017].

[12] R. . Ewing, "Impacts of Traffic Calming (A Peer-Reviewed Paper)," *Transportation Quarterly,* vol. 55, no. 1, pp. 33-45, 2001.

[13] S. Grosso, S. Wright and M. G. Bell, "Evaluating the environmental impact of traffic calming," *Traffic engineering and control,* vol. 43, no. 6, pp. 238-243, 2002.

[14] A. . Hadayeghi, B. . Malone and S. . McIntyre, "Impact of Road Lane Narrowing Traffic Calming Treatments on Speed and Volume," , 2006. [Online]. Available: http://conf.tac-atc.ca/english/resourcecentre/readingroom/conference/conf2006/docs/s017/haday.pdf. [Accessed 4 7 2018].

[15]   K. . Ahn and H. . Rakha, "Energy and Environmental Effects of Traffic Calming Measures," , 2008. [Online]. Available: https://trid.trb.org/view.aspx?id=847820. [Accessed 4 7 2018].

[16]   U. Petruccelli, "TRAFFIC CALMING: A REVIEW OF TECHNIQUES AND THEIR EFFECTIVENESS," *Traffic engineering and control,* vol. 41, no. 11, pp. 458-464, 2000.

[17]   R. Ewing and C. Kooshian, "U.S. EXPERIENCE WITH TRAFFIC CALMING," *Ite Journal-institute of Transportation Engineers,* vol. 67, no. 8, pp. 28-33, 1997.

[18]   K. A. Harder and J. T. Carmody, "INVESTIGATING THE EFFECTS OF TRAFFIC CALMING STRATEGIES ON DRIVER BEHAVIOR," , 2002. [Online]. Available: https://conservancy.umn.edu/handle/11299/763. [Accessed 3 7 2018].

[19]   A. Książek, "Approach to Simulation Assessment of Area-wide Traffic Calming in the Context of Sustainable Development," *WIT Transactions on the Built Environment,* vol. 146, no. 146, pp. 191-203, 2015.

[20]   G. . Ghafghazi and M. . Hatzopoulou, "Simulating the Environmental Effects of Isolated and Area-wide Traffic Calming Schemes Using Traffic Simulation and Microscopic Emission Modeling," , 2013. [Online]. Available: https://trid.trb.org/view/1240935. [Accessed 29 6 2018].

[21]   S. . Caprì, M. . Ignaccolo and G. . Inturri, "Evaluating the Effectiveness of Traffic Calming Devices: Using Simulation to Overcome Analytical Models Assumptions," , 2012. [Online]. Available: http://article.sapub.org/10.5923.j.ijtte.20120103.03.html. [Accessed 2 10 2017].

[22]   Parvathy N., Bindhu B. and Elangovan T., "Impact of Analysis of Speed Restriction Meausures using VISSIM 5.40," *International Journal of Innovative Research on Energy and Environment,* 2013.

[23]   R. . Rossi, M. . Gastaldi, G. . Gecchele, F. . Biondi and C. . Mulatti, "Traffic-Calming Measures Affecting Perceived Speed in Approaching Bends: On-Field Validated Virtual Environment," *Transportation Research Record,* vol. 2434, no. 2434, pp. 35-43, 2014.

[24]   F. . Galante, F. . Mauriello, A. . Montella, M. . Pernetti, M. . Aria and A. . D'Ambrosio, "Traffic calming along rural highways crossing small urban communities: Driving simulator experiment," *Accident Analysis & Prevention,* vol. 42, no. 6, pp. 1585-1594, 2010.

[25]   F. Bella, "Driving Simulator for speed research on two-lane rural roads," *Accident analysis and preventation,* vol. 40, 2008.

[26]   H. . Chen, X. . Zhang and G. . Liu, "Simulation and Visualization of Empirical Traffic Models Using VISSIM," , 2007. [Online]. Available: http://dblp.uni-trier.de/db/conf/icnsc/icnsc2007.html. [Accessed 30 9 2017].

[27]   K. Ozbay, H. Yang, S. Mudigonda, B. Bartan and F. E. Morgul, "Big Data and the Calibration and Validation of Traffic Simulation Models," *Transportation Research E-Circular,* no. E-C195, 10 June 2015.

[28]   J. Taplin, "Simulation Models of Traffic Flow".

[29]   B. Mathhew, K. Davis, D. Kieninger, K. Mizuta and E. Robinson, "A Guide to
         Documenting VISSIM-Based Microscopic Simulation Models," Washington,
         2007.

[30]   PTV AG, Ptv Vissim 8 User Manual, 2015.

[31]   ptv vision, VISSIM-State-of-the-Art Multi-Modal Simulation, 2009.

[32]   A. M. Monatasir, A. Medina and B. Higgs, "Analysis of the Wiedemann Car Following
         Model over Different Speeds using Naturalistic Data," 2011.

[33]   TRB, Highway Capacity Manual:A Guide for Multimodal Mobility Analysis, vol. Sixth
         Edition, Washington, D.C: National Research Council, 2016.

[34]   A. García, A. J. Torres, M. Romero and A. T. Moreno, "Traffic Microsimulation Study to
         Evaluate the Effect of Type and Spacing of Traffic Calming Devices on
         Capacity," *Procedia - Social and Behavioral Sciences,* vol. 16, pp. 270-281,
         2011.

[35]   H. . Shirmohammadi, E. . Mardani, M. E. Ghane and A. . Hasheminezhad, "Simulating
         the Effects of Type and Spacing of Traffic Calming Measures on Urban Road
         Capacity," , 2018. [Online]. Available:
         http://ijte.ir/article_50736_ece0f7f71a794a4b127cd367bfd995cf.pdf. [Accessed 4
         7 2018].

[36]   A. D. May and E. M. K. Harmut, "NON-INTEGER CAR-FOLLOWING MODELS,"
         Highway Research Record, vol. , no. 199, p. , 1967.

[37]   R. P. Roess, E. S. Prassas and W. R. McShane, Traffic engineering, London: Prentice
         Hall, 2004.

[38]   B. . Greenshields, J. . Bibbins, W. . Channing and H. . Miller, "A STUDY OF TRAFFIC
         CAPACITY," , 1935. [Online]. Available:
         https://safetylit.org/citations/index.php?fuseaction=citations.viewdetails&citationi
         ds[]=citjournalarticle_248667_38. [Accessed 4 7 2018].

[39]   D. R. Drew, Traffic flow theory and control, New York: McGraw-Hill Book Company,
         1968.

[40]   R. Underwood, "Speed, Volume and Density Relationships," *Quality and Theory of
         Traffic Flow,* pp. 143-188, 1960.

[41]   J. L. Drake and J. L. Schofer, "A Statistical Analysis of Speed-Density Hypotheses,"
         Highway Research Record, vol. , no. , pp. 53-87, 1966.

[42]   J. . Laufer, "Freeway capacity, saturation flow and the car following behavioural
         algorithm of VISSIM microsimulation software," , 2007. [Online]. Available:
         https://trid.trb.org/view/2007/c/855234. [Accessed 4 7 2018].

[43]   G. . Lee, S. . Joo, C. . Oh and K. . Choi, "A Comprehensive Evaluation Framework of
         Traffic Calming Measures in Residential Areas," , 2013. [Online]. Available:
         https://trid.trb.org/view.aspx?id=1241943. [Accessed 4 7 2018].

[44]   Miovision, "Miovision Scout," [Online]. Available: https://miovision.com. [Accessed
         2018 9].

[45]   [Online]. Available:
         https://www.gps.gov/multimedia/presentations/2014/09/ION/bunce.pdf.
         [Accessed 17 9 2018].

[46] R. P. Roess, "Traffic engineering / Roger P. Roess, Elena S. Prassas, William R. McShane," , 2004. [Online]. Available: http://library.um.ac.id/free-contents/downloadpdf.php/buku/traffic-engineering-roger-p-roess-elena-s-prassas-william-r-mcshane-30688.pdf. [Accessed 4 7 2018].

[47] FHWA, "FHWA's Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software," 2004.

[48] B. Park and Q. H, "Development and Evaluationof Simulation Model Calibration Procedure," *Journal of the Transportation Research Board 1934,* 2005.

[49] K. S. Shabaan and E. Radwan, "A calibration and validation procedure for microscopic model:a case study of sim traffic arterials streets.," in *Proceedings of the 83rd TRB Annual Meeting*, Washington, DC, 2005.

[50] D. Gazis, R. Herman and R. Rothery, "Nonlinear follow-the-leader models of traffic flow," *Operations Research,* vol. 9, no. 4, pp. 545-567., 1961.

[51] D. Braess, A. Nagurney and T. Wakolbinger, "On a paradox of traffic planning," *Transportation science,* vol. 39, no. 4, pp. 446-450, 2005.

[52] A. Downs, Still stuck in traffic: coping with peak-hour traffic congestion, Brookings Institution Press, 2005.

[53] M. J. H. Mogridge, Travel in towns: jam yesterday, jam today and jam tomorrow?, Springer, 1990.

[54] J. A. Rosales and K. K. Knapp, "Livability Impacts of Geometric Design Cross-Section Changes from Road Diets," 2005.

[55] H. F. Huang, J. R. Stewart and C. V. Zegeer, "Evaluation of lane reduction "road diet" measures on crashes and injuries," *Transportation Research Record,* vol. 1784, no. 1, pp. 80-90, 2002.

[56] M. D. Pawlovich, "Iowa's Experience with "Road Diet" Measures: Impacts on Crash Frequencies and Crash Rates Assessed Following a Bayesian Approach. Transportation Research Record," 2006.

[57] W. Li, A. Carriquiry, M. Pawlovich and T. Welch, "The choice of statistical models in road safety countermeasure effectiveness studies in Iowa," *Accident Analysis & Prevention,* vol. 40, no. 4, pp. 1531-1542, 1 7 2008.

[58] K. K. Knapp and K. Giese, "Guidelines for the conversion of urban four-lane undivided roadways to three-lane two-way left-turn lane facilities," 2001.

[59] R. Anderson, "Regional Road Diet Analysis – A Feasibility Assessment".

[60] H. Li and Z. Tian, "Feasibility Evaluation of Road Diet Projects–A Case Study in Reno, NV".

[61] R. B. Noland, D. Gao, E. J. Gonzales, C. Brown, G. Patterson and A. M. Voorhees, "Costs and Benefits of a Road Diet for Livingston Avenue in New Brunswick, New Jersey," 2014.

[62] N. Stamatiadis and A. Kirk, "Simulation-based guidelines for road "diets" Using Mobile Devices for Safety Performance Measures View project Surrogate Measure of Safety View project Simulation-based guidelines for road "diets"," *Advances in Transportation Studies an international Journal 2014 Special Issue,* vol. 2.

[63] K. K. Knapp, K. L. Giese and W. Lee, "Urban Four-Lane Undivided to Three-Lane Roadway Conversion Guidelines," 2003.

[64] A. K. Civil, E. Engineering, U. Amherst, E. J. Gonzales and A. Keegan, "Evaluation of Urban Freight Deliveries using Microsimulation and Surrogate Safety Measures," 2018.

[65] "Bus Stop Safety and Design Guidelines," 2004.

[66] "Bus Stop Specification Guidelines," 2016.

[67] "Road Diet Recipe: Dedicated Bus Lane Shortens Morning Commute | EfficientGov," [Online]. Available: https://efficientgov.com/blog/2018/06/15/road-diet-recipe-dedicated-bus-lane-shortens-morning-commute/.

[68] "Road Diets: Reconfiguring the Road for Safety," [Online]. Available: https://www.snyder-associates.com/2018/09/10/road-diets-improve-traffic-safety/.

[69] L. Pu, R. Joshi and S. Energy, "Surrogate Safety Assessment Model (SSAM)--software user manual," Turner-Fairbank Highway Research Center, 2008.

[70] D. Gettman, L. Pu, T. Sayed, S. Shelby and I. T. S. Siemens, "Surrogate safety assessment model and validation," United States. Federal Highway Administration. Office of Safety Research and …, 2008.

[71] Å. Svensson, "A method for analysing the traffic process in a safety perspective," 1998.

[72] Z. A. Sabra, D. Gettman, R. D. Henry, V. Nallamothu and W. &. A. I. Sabra, *Balancing Safety and Capacity in an Adaptive Signal Control System — Phase 1,* United States. Federal Highway Administration, 2010.

[73] PTV, "PTV VISSIM 10 USER MANUAL," 2018.

[74] M. Fellendorf and P. Ag, Integrated Modeling of Transport Demand, Route Choice, Traffic Flow and Traffic Emissions, 2001, p. .

[75] "Nashville > Public Works," [Online]. Available: https://www.nashville.gov/Public-Works.aspx.

[76] K. Fitzpatrick and R. L. Nowlin, "Effects of bus stop design on suburban arterial operations," *Transportation Research Record,* vol. 1571, no. 1, pp. 31-41, 1997.

[77] R. Z. Koshy and V. T. Arasan, "Influence of bus stops on flow characteristics of mixed traffic," *Journal of transportation engineering,* vol. 131, no. 8, pp. 640-643, 2005.

[78] J. Sacks, N. M. Rouphail, B. Park and P. Thakuriah, "Statistically-based validation of computer simulation models in traffic operations and management," *Journal of Transportation and Statistics,* vol. 5, no. 1, pp. 1-24, 2002.

[79] S. Moridpour, M. Sarvi and G. Rose, "Modeling the Lane-Changing Execution of Multiclass Vehicles under Heavy Traffic Conditions," *Transportation Research Record,* vol. 2161, no. 1, pp. 11-19, 1 1 2010.

[80] V. Ramanujam, "Lane Changing Models for Arterial Traffic," 2007.

[81] Y. Gao, H. Rakha, M. Abbas and A. A. T. Member, "Calibration and Comparison of the VISSIM and INTEGRATION Microscopic Traffic Simulation Models," 2008.

51

[82] M. Fellendorf and P. Vortisch, "Microscopic traffic flow simulator VISSIM," in *Fundamentals of traffic simulation*, Springer, 2010, pp. 63-93.

[83] J. Bonneson and J. Ivan, "Theory, Explanation, and Prediction in Road Safety: Promising Directions," *Transportation Research Circular,* no. E-C179, 2013.

[84] C. Wang and N. Stamatiadis, "Surrogate safety measure for simulation-based conflict study," *Transportation research record,* vol. 2386, no. 1, pp. 72-80, 2013.

[85] "E-TRIMS Logon," [Online]. Available: https://e-trims.tdot.tn.gov/Account/Logon?url=http%3a%2f%2fe-trims.tdot.tn.gov%2f.