Factors Affecting Operating Speed on Urban Tangent Road Sections

by

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Abstract

This thesis expands previous research on operating speed models by developing models for tangent segments in an urban road environment. The thesis explored the relationships between operating speeds and several road features which have not been previously investigated. Typically, operating speed models use a single operating speed such as the 85th percentile. The single percentile approach is limiting as it narrows the data set and does not represent the entire speed profile. Panel data allows for the use of multiple operating speed percentiles. To overcome this limitation, this thesis used panel data representing speed percentiles from 5 to 95 in increments of 5. Panel data not only increases the data set but allows the impacts of operating speed and speed variability to be investigated separately. Furthermore, several class variables were added to model to allow for variation within a single attribute to be explicitly modeled as opposed to the standard binary operator approach.

This thesis is a large exhaustive macro evaluation of urban roads using 280 tangent locations. The data set is comprised of 31 residential, 123 collector and 126 arterial roads. In order to study the impact of road elements on different road types, four models were created: one model was created to include all locations, a separate model that only included arterial and collector locations, another model that included only arterial locations, and a final model with only collector locations. The models resulted in several interesting findings:

- Operating speeds on one-ways were lower than two-way roads.

- Roads with sidewalks that were farther away from the road were associated with higher operating speeds.
- Locations with monolithic walk on both sides of the road had the lowest operating speeds.
- Roads that had bicycle facilities were associated with higher operating speeds.
- Longer road segments had higher operating speeds.
- Operating speeds decreased as accesses increased.
- On arterials, operating speeds decreased as object density and/or tree density increased.
- Bus stops were found to have opposite effects on arterials compared to collectors. On arterials bus stops were associated with higher operating speeds while on collectors they were associated with lower operating speeds.
- A wider median, on arterials, was associated with higher operating speeds.

The findings from this thesis expanded the current understanding of the effect of elements in the urban environment on operating speeds. One of the major takeaways was that the elements which were statistically significant differed between road classes.

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List of Abbreviations and Symbols

AASHTO	American Association of State Highway Transportation Officials
ANN	Artificial Neural Network
BPN	Back propagation artificial neural network
DCM	Design Consistency Model
FHWA	Federal Highway Administration
GLM	General linear model procedure from SAS
OLS	Ordinary least squares
OSL-PD	Ordinary least squares panel data
PD	Panel data
REG	Regression procedure from SAS
RHR	Roadside hazard rating
SAS	Statistical Analysis System (Software)
TAC	Transportation Association of Canada
TRB	Transportation Research Board of the National Academies
V_{85}	85^{th} percentile speed
V_{95}	95^{th} percentile speed
Z_p	The normally distributed z value associated with a given percentile values

1 Introduction

1.1 Background

Operating speed models influence the design of traffic flow network models, emissions models, road design, design consistency, and traffic safety. Most urban traffic network models rely on existing traffic flow data as inputs. However, in the absence of such data, network modellers are required to make assumptions regarding vehicle operating speeds. Operating speed models would help refine such assumptions. Urban operating speed models would also improve network planning as road design elements would feedback into the model giving more realistic results. Operating speed models would have similar contributions in setting operating speeds in emission models.

Currently in North America geometric road design typically only considers minimum designs speeds. Where possible, designers are encouraged to adopt higher standard to increase the factor of safety *(1)*. This design approach can lead to a dichotomy between successive elements as minimum design speeds are typically only one factor on vertical and horizontal curves, whereas tangent or straight sections can often be over designed when operating speed is considered.

Design consistency, as Cafiso and Cerni point out in their 2012 paper, is designing the road in such a way as to reduce driver error. Design consistency is typically controlled by designing for the operating speed *(2)*. Studies have shown that collisions increase with change in operating speed between successive road elements *(1, 3)*. Some jurisdictions in Europe have started to change their design approaches to incorporate design consistency between elements. In North America, design consistency is mentioned in American Association of State Highway Transportation Officials (AASHTO) and Transportation Association of Canada's (TAC) design guides. However, neither association explicitly calls for design consistency to be controlled for *(1)*.

With respect to road design, jurisdictions such as the City of Edmonton in Canada, are moving towards a 'complete streets' design standard. The goal of complete streets is to consider all users of a corridor during design. On arterials, the complete streets design approach is moving away from a car centric design by setting the design speed as the posted speed limit, allowing narrower lanes, allowing on street parking, targeting reduced pedestrian crossing distances, and supporting roundabouts. In such an approach knowing how design elements affect operating speeds will only serve to better the design.

With regards to traffic safety, ‘speed has been found to be a statistically significant contributory factor for the number and consistency of crashes…’*(4)*. When looking at design consistency, Wu et al. found that there was an ‘association’ between design consistency and safety *(5)*. And narrowing the focus even further, Watson et al. found that the frequency of crashes increases the greater the free-flow speeds exceed the design speed or posted speed limit*(6)*. These issues have a twofold solution: enforcement and design. Traditionally the focus has been on enforcement to solve speeding. However, on some road sections, enforcement only temporarily reduces operating speeds. Some roads (or road sections) need to be redesigned to more closely match the desired operating speeds. Currently in an urban environment, there is very little information to base these design changes on.

To date most operating speed models have focused on two lane rural highways and specifically curves on roads. The literature has shown that operating speeds on curves are closely linked to the radius of the curve or variations thereof. Few studies have examined tangents and even fewer have focused on tangents in urban areas.

1.2 Research Problem Statement

Which factors impact a driver’s chosen speed on straight (tangent) urban roads? How much do these elements impact operating speeds? How does this vary between arterial and collector roads? And how should the geometry and road elements be changed to reduce operating speeds on an arterial or collector? Answering the abovementioned questions form the basis and premises of this thesis.

1.3 Research Motivation

The current trend in urban road design is to design roads a little less car centric and design for all right-of-way users. These design practices are called complete streets or, sometimes on existing roads, road dieting. These general design principles often lead to reduced lane widths, more planted areas, wider sidewalks, introduction of bike lanes, and better crosswalks. An underlying goal of such changes is often to reduce operating speeds. However, only two studies have looked at how elements of the urban roadway affect operating speed. These studies were not expositive and only used binary variables. This study is intended as a more comprehensive overview of the elements available to an urban road designer and to gauge their impact on operating speeds.

1.4 Research Objective

Significant research has been conducted on road features and their impacts on drivers' speed. The majority of this work focused on two lane rural highways, particularly at horizontal curves. Most recently, studies have been conducted in urban areas to examine all classifications of roads. In both subsets, the least studied sections of roadways are tangents.

Unlike curve operating speed models, which are typically defined by a variable that is a variation of the curve radius, many road parameters affect tangent operating speeds. The number of parameters and the difference in study sites resulted in many variations in tangent speed models. Some studies focused on one key variable, while others included as many road features as possible. This also resulted in differing conclusions between tangent operating speed studies.

Tangent operating speed models are divided into two general groups: those that use the posted speed limit as the main determinant variable and those that focus on other road characteristics. Typically, the latter have significantly more variables, which may or may not include the posted speed limit.

This thesis will expand the research on urban tangent operating speed models by:

- Exploring the effects of certain roadway features on operating speeds for urban tangents. To achieve this objective, the following sub-objectives were defined:
    - Conduct a thorough literature review to identify key features that were found to be statistically associated with operating speed.
    - Study the effect of additional variables which have not been included in previous models.
    - Assemble a large urban data set (including data on speeds, geometry, roadside features, etc.) into different models based on road classification. This will show how road features impact road classes differently and which features have similar impacts across all road classes.
- Exploring the use of Panel Data to estimate speed profiles over a single point estimate by applying the latest speed modeling techniques.

1.5 Thesis Structure

This thesis will first review all the literature on operating speed models. The two focuses of this review will be to i) determine the types of models that have been developed and ii) identify which variables were studied and what impact they had on operating speed. The literature review will concentrate on other tangent models with special attention on urban models. Chapter three will then discuss the methodology of how data from 280 road locations, mostly arterial and collector tangent sections, were modeled using panel data and class variables. Chapter four will discuss the findings from this thesis. Chapter five will summarize the key findings, offer closing remarks, and make recommendations for further studies.

2 Literature Review

This literature review largely focuses on tangent operating speed models from urban studies. Since the majority of studies to-date have focused on two-lane rural highways or curved sections, information will also be presented from these types of facilities. This review will examine model estimation techniques with examples, followed by a discussion on the variables that have been used in published models.

2.1 Existing Model Forms

Most operating speed models were developed using Ordinary Least Squares (OLS) estimation technique. In the 2011 TRC Synthesis Report on Operating Speed, 21 of the 23 used OLS to develop their models *(7)*.

While OLS remains the most prevalent model estimation technique, some researchers have found that OLS estimation has certain shortcomings, particularly when used in the urban environment. To that end, researchers have started using alternate modeling techniques to address some of the limitations of models developed with OLS. In the Synthesis Report *(7)*, the two alternate estimating forms were ordinary least squares panel data (OSL-PD) and a back propagation artificial neural network (BPN). Since 2011, two additional estimating techniques were used on operating speed models: simultaneous equations and Panel Mixed Probit Fractional Split Model.

2.1.1 Ordinary Least Squares

As previously mentioned, OLS estimation is the most prevalent method of fitting speed data to a given data set. The OLS approach fits a function to data by minimizing the sum of the squares. The OLS technique has the least amount of error when the variables are exogenous and do not exhibit multicollinearity *(8)*. Models using OLS work best when they consist of variables that are not influenced by the model or each other.

Multicollinearity is often a source of concern in operating speed models. The concern is that, because roadways use a design speed to determine geometric feature and posted speed limit, these features are correlated. Several authors, including

Fitzpatrick et al. (2001) and Lobo et al. (2013), explored this issue and evaluated all variables for collinearity. Variables containing collinearity were either combined into a single variable or one of the variables was removed *(9, 10)*. Himes and Donnell (2013) specifically delved into whether the posted speed limit should be included in the model—this will be discussed later in this analysis*(11)*.

The aggregation of data is another limitation of OLS estimation. Aggregation is an issue when operating speed models are reduced to a single percentile speed value. Results in the unique speed profile of the road section being studied not being represented in the model. Additionally, when the data is aggregated, it is impossible to evaluate the impact of the speed distribution. One option in handling data aggregation is to use panel data. This will be discussed in the OLS-PD section.

Following are models that were developed using the OLS technique:

2.1.1.1 Highway Tangent Models Using Curve Data 2000

One of the earlier tangent models was for two-lane rural highways and primarily defined operating speed on a tangent by the preceding and receding curves. Using radar, the data was collected from six American states: Minnesota, New York, Pennsylvania, Oregon, Washington, and Texas. In collecting data, the authors were looking for sites that had minimal cross sectional variations, which included access density. "The general criteria used to identify sites […] represents the most common conditions found in the United States. For example, the database included roads with few access points […]." The road sections had speed limits between 75 and 115 km/h. To account for free flow conditions, the authors searched for locations with volumes lower than 2,000 vehicles per day *(12)*.

The roads selected in this study were not urban arterials or collectors. However, this study is significant because it demonstrates the more standard two-lane rural highway focus of most operating speed studies. Equally important, it highlights that most models to-date have been focus on developing operating models for horizontal curves.

In conjunction with the before and after curve data and tangent length, the authors evaluated longitudinal grades, "cross-sectional characteristics", presence of spirals, topography, and “overall alignment characteristic […] such as average horizontal curvature and average slope.”

The authors separated the tangent sections into four groups all based on radii size and tangent length. For instance, Group 1 is, “small radii and small [tangent length],” and Group 4 is, “[l]arge [tangent length] and any reasonable radius.”

The model was derived using ordinary least-squares regression to fit curves to the 85th percentile speed data and “Geometric Measure ($GM_{S/L}$)”. The GM_S for short tangents was $(R_1+R_2)/2$ where R represents the radius of the curves into and out of the tangent. The GM_L for long tangents was $[TL\ (R_1 \text{x} R_2)^{1/2}]\ /100$ where, again, R was the radius in and out and TL was the tangent length.

2.1.1.2 Urban Tangent Model, Ali et al. 2007

Ali et al.’s (2007) model is included in the 2011 TRC Synthesis Report on Operating Speed. The authors examined the correlations between road features and operating speed *(7)*.

The speed data used was from “35 four-lane urban streets in Fairfax County, Virginia.” The posted speed limits were between 35 and 45 mph (56 and 72 km/h, respectively). The speed data was collected using radar guns at midblock locations across 35 sites. At each site, the authors collected between 26 and 61 free flow spot speeds. The total data set included 1,742 speed data points.

In their study, the authors looked at: “posted speed, lane width, median type, median width, access density,” adjacent land use, and segment length. The authors found that the major factors affecting operating speed were: “posted speed, median width, and segment length […].” Two models for 85th percentile operating speed were created using linear regression:

$$FFS_{85} = 42.3 + 10.4\ PS_{45} + 3.8\ PS_{40} \quad [1]$$

$$FFS_{85} = 37.4+8.0PS_{45}+2.1PS_{40}+3.6MT+13SL \quad [2]$$

where

FFS_{85} = the 85th percentile free-flow speed (mph);

PS_{45} = posted speed (1 if posted speed is 45; 0 otherwise, baseline 35);

PS_{40} = posted speed (1 if posted speed is 40; 0 otherwise, baseline 35);

SL = segment length ratio; and

MT = median type (1 if divided or two-way left-turn lane; 0 if no median).

2.1.1.3 Fitzpatrick et al. Urban Tangent Model

Kay Fitzpatrick and other researchers have proposed several urban tangent models in different studies and publications.

2.1.1.3.1 Suburban Streets Study 2001

In 2001, Fitzpatrick et al. looked at suburban arterials in six cities across Texas. The study evaluated both horizontal curves (19 sites) and tangent sections (36 sties). In choosing sites, the authors removed the impact of grade, looking for sites with grades between +4% and -4%. The data was collected using a radar gun *(9)*.

As the study was focused on geometric features and all the sites were arterials, the authors were concerned about correlation between variables and sites. In order to assess the impact of multicollinearity on the variables, the authors used “Statistical Analysis System (SAS) and the proc CORR command.” The CORR process indicated several correlated variables. The authors then adjusted the model by removing any correlated variables. In their study there were several variables which represented attributes of the curved section of road which were correlated. With respect to variables representing the tangent sections, only the lane widths correlated. To remove this collinearity issue, a single lane width was used—an average of all the lane widths on that given study section.

When examining tangent sections, “[m]ultiple regression techniques from SAS (pro REG and proc GLM) were used to determine how the variables within each category of data affect speed.” Using this technique, they found that lane widths and posted speed limit were the only two statistically significant factors. They did not find that road side features impacted speed.

2.1.1.3.2 Operating Speed and Tangents 2005

In 2005, Fitzpatrick et al. specifically examined operating speeds on tangents. This time, they expanded their study to 79 locations in seven Cities across six states (Little Rock, Ark.; St. Louis, Mo.; Nashville, Tenn.; Portland, Ore.; Boston, Mass.; and College Station and Houston, Tex.). The study looked at arterials, collectors, and local roads. Again, largely flat sites were selected with grades between +4% and -4% *(13)*.

The data was collected using radar guns on weekdays between 7:00 am and 6:00 pm when pavement conditions were dry. Only free flow data with a five second headway and a three second tailway was used. A data set at any given site had to contain a minimum of 100 vehicles or a minimum of four hours of data.

The analysis studied the statistical significance of the number of lanes, lane width, total pavement width, access density, shoulder type (none, curb and gutter, flush), parking, bike lane, median type, median width, signal density, and distance between features (e.g., signals or horizontal curves). Some of these variables were associated with higher speeds, such as longer distance between features, large shoulder, wider road, and a wider median. Other features were associated with lower speeds, including shorter signal density, absence of centerline, on street parking, and no median. While these variables were associated with higher or lower operating speed, only the posted speed limit was "statistically significant at a 5% alpha level." When the t statistic was considered, the only other statistically significant variable was access density with a t value of -1.31. Linear regression was used to find the relationship between the posted speed, access density, and operating speed. Following are the equations:

$$FF85 = 12.4 + 0.98(SL) \quad [3]$$

$$FF85 = 25.9 + 0.83(SL) - 0.054(AD) \quad [4]$$

where

$FF85$ = free-flow 85th percentile speed (km/h);

SL = posted speed limit of 73 km/h or less (km/h); and

AD = access density, number of access points per 1.6km.

2.1.1.4 Interactive Highway Safety Design Model (IHSDM)

The IHSDM is a collection of programs released by the US Department of Transportation's Federal Highway Administration. It is intended to support the design of highways. The IHSDM includes six modules: "Crash Prediction, Design Consistency, Intersection Review, Policy Review, Traffic Analysis, and Driver/Vehicle." The Design Consistency Model (DCM) predicts operating speeds *(14)*.

Prior to the 2010 edition, the DCM was designed for roads with speeds of 55 mph (88 km/h) but worked reasonably well down to 60 km/h. The 2010 release included models that where created using lower speed road sections (25 to 40 mph or 40 to 65 mph). The lower speed DCM uses different models depending on the length of tangent. For tangents shorter than 150 feet, the model calculates the value of V_{T85} based on the radius and posted speed limit. The model uses the following equation for tangent sections greater than or equal to 150 feet *(7)*:

$$V_{T85} = 26.04 + 0.53PS - 0.89RHR + 0.005LT \qquad [5]$$

where

LT = length of tangent (ft) (Note: use LT = 1,000 ft for tangent lengths greater than 1,000 ft);

PS = posted speed (mph); and

RHR = roadside hazard rating (1 to 7). Report FHWA- RD-99-207, **Appendix D** provides a guide for calculating the RHR.

2.1.2 Linear Mixed-Effect Model Using OLS Estimation

2.1.2.1 Urban Tangent Model Using GPS, 2006

Wang et al.'s (2006) model focused on creating a continuous operating speed profile and quantifying the impact of geometric features in low speed urban settings *(15)*.

The data for this model was collected on urban arterial, collector, and residential streets in Atlanta, Georgia, USA. The studied streets had speed limits under 40 mph (65 km/h). The authors selected 35 tangent corridors based on number of trips by drivers and the uninterrupted tangent length between two intersections. The data set was further refined using speed thresholds to account for turning vehicles or vehicles that slowed down for other reasons. Trips that occurred under rainy conditions were also removed.

The data was collected using Global Positioning (GPS) devices in 200 vehicles with drivers aged between 18 and 60. The distribution of drivers was matched to the distribution of licensed drivers as reported by US Federal government in 2003. The vehicles used were "passenger cars, minivans, SUVs, and pickups." As given data sets only show data for a single vehicle, off peak trips were used to best represent free-flow condition.

This study used a linear mixed effects model because speed profiles of individual vehicles and drivers would be correlated between different locations. Models were built for each driver across several road sections. Using the same driver on multiple road sections allowed the authors to partially control for driver variability.

The model used the form:

$$y_{ij} = \beta_0 + v_{0i} + \beta_1 X_{1j} + \beta_2 X_{2j} + \ldots + \beta_p X_{pj} + \varepsilon_{ij} \quad [6]$$

where

y_{ij} = speed of drive i on road section j;

β_0 = mean speed across all drivers;

v_{0i} = random variable for each driver i which accounts for the random effects of each driver and vehicle, $v_{0i} \sim N(0,\sigma_v^2)$;

β_i = coefficient for geometric feature i;

X_{pj} = geometric feature variable;

ε_{ij} = error normally distributed, $\varepsilon_{ij} \sim N(0,\sigma^2)$;

σ^2 = variance for a given driver and vehicle; and

σ_v^2 = variance between drivers and vehicles.

The authors also used the statistical significance of each variable to determine whether it should be included in the model. They did this with a forward stepwise regression, where variables were added one at a time base on their statistical significance. Only variables that were 95% significant were used. Through this process, they found that the statistically significant variables included the number of lanes, density of roadside objects, density of driveways, T-intersection density, the presence of a curb, the presence of a sidewalk, the presence of parking, and land use type.

Following is the final 85^{th} percentile operating speed model:

$$V_{85} = 31.565 + (6.491 \times lane.num) - (.101 \times roadside) - (.051 \times driveway) - (.082 \times intersection) + (3.01 \times curb) - (4.265 \times sidewalk) - (3.189 \times parking) + (3.312 \times land.use1) + (3.273 \times land.use2) \quad [7]$$

Based on their research, the authors settled on three interesting conclusions:

1. Posted speed should not be included in the model as it is too closely correlated to other variables.
2. Drivers don't always reach their peak speed at the midpoint of a tangent section.
3. The driver and vehicle were responsible for 35% of the unexplained variance.

The linear mixed-effects model worked well for Wang et al.'s data set and study. However, this type of model does not effectively extend to non-GPS based operating speed models. In Wang et al.'s model, they dealt with individual GPS data sets that extended across multiple road sections. For the analysis, they set the speed of the vehicle and the geometric features as fixed effects and allowed the driver and vehicle to be random effects. The study used a set of 200 personal vehicles and drivers. The random sample was compared to the 'U.S. census data of licensed drivers in 2003' and was found to be similarly distributed.

2.1.3 Ordinary Least Squares Panel Data (OLS-PD)

Panel data (PD) can be used in conjunction with OLS to address the OLS limitations of aggregation and speed distribution. Models which use traditional OLS estimation generate a single value for the 85^{th} or 50^{th} percentile speed. Conversely, models using

OLS-PD can produce speeds for any percentile or range thereof. This allows the model to be used to predict the speed at given percentiles as well as the distributions of speeds across the entire flow. The distribution of speed is important because it allows researchers to, "separate the impacts on mean speed from the impacts on speed dispersion" *(7)*. Himes, Donnell and Porter *(16)* agreed with the conclusion and recommended that the speed dispersion is important to include in future models.

OLS-PD estimation also go further in reducing collinearity by increasing the degrees of freedom. Figueroa, Medina and Tarko, who used OLS-PD estimation, found that while there was, "considerable correlation between model variables, there was no multicollinearity between the variables, and no variables had to be removed to enable the model estimation"*(17)*. The downside of raising the degrees of freedom is that it significantly increases the amount of data required.

The 2011 Synthesis Report recommended introducing a "site-specific and percentile-specific random effects" for models using OLS-PD estimation. Adding these to random effects variables would "avoid bias in estimating the model parameters caused by unknown factors not incorporated in the regression model" *(7)*.

2.1.3.1 Highway Tangent Model 2005

Figueroa et al.'s (2005) tangent speed highway model was the first use of PD for operating speed *(17)*.

Data was collected at 158 locations on two-lane rural highways segments throughout Indiana using a radar gun. The study evaluated terrain, grade, sight distance, road surface, speed limit, density of residential development, carriageway width, shoulder width, roadside obstructions, horizontal curve data, and intersection data. Only free-flow data was used. The minimum number of vehicles' speed data collected per location was 100, with an average number of 360.

The model used OLS regression applied to PD (OLS-PD). The PD part of the model divides all vehicles into their "[p]ercentile of speeds from the 5^{th} to the 95^{th} percentile, in increments of five […]." The goal of using PD is to reduce collinearity between the variables by increasing the degrees of freedom. PD accomplishes this by have a larger data set then other data sets. Flowing is the model:

$$Vp = 57.137 - 0.071(TR) - 3.082(PSL_{50}) - 0.131(GR) - 1.034(RES) + 2.3810^{-3}(SD) - 1.67\times10^{-6}(SD)^2 - 0.422(INT) + 0.040(PAV) + 0.394(GSW) + 0.054(USW) - 2.233(FC) + 5.982(Zp) + 1.428(Zp \times PSL_{50}) + 0.061(Zp \times GR) + 0.292(Zp \times INT) - 0.038(Zp \times PAV) - 0.012(Zp \times CLR) \quad [8]$$

where

TR = percentage of trucks;

PSL_{50} = equal to 1 if the posted speed limit is 50mph, and equal to 0 if the posted speed limit is 55 mph;

GR = highway grade (%);

RES = equal to 1 if the segment has 10 or more residential drive- ways per mile, 0 otherwise;

SD = sight distance (ft);

INT = equal to 1 if an intersection is located 350ft before or after the spot, 0 otherwise;

PAV = pavement width, includes the traveled way and both paved shoulders (ft);

GSW = total gravel shoulder width (ft);

USW = total untreated shoulder width (ft);

CLR = roadside clear zone, includes the total gravel and total untreated shoulders (ft);

FC = equal to 1 if the spot is located on a flat curve (radius larger than 1,700ft), 0 otherwise; and

Z_p = standardized normal variable corresponding to a selected percentile.

2.1.4 Simultaneous Equations - OLS

Only one study has used simultaneous equations and OLS. The authors used simultaneous equations to study the dependency (endogeneity) between different lanes on a four-lane highway.

2.1.4.1 Urban Residential 30km/h 2013

Dinh and Kubota (2013) conducted their study on 85 streets in the Cities of Saitama, Kawaguchi, and Warabi in the Saitama Prefecture of Japan. They collected the data using a radar gun on streets with a speed limit of 30 km/h. A minimum of 70 vehicle speed profiles were collected at each site for a total of 5359 speed profiles across all sites *(16)*.

The geometric features considered in the study included length of street, number of lanes, lane width, carriageway width, left safety strip width, right safety strip width, centerline, sidewalk width, roadside object density, driveway density, land use, type of intersections (at both ends and along the study section), pedestrian crossing, width of crossing street, and ratio between crossing street and study street.

The model was comprised of four equations: two were for the operating speed in lanes one and two, and the remaining two equations were for the speed deviation in each lane. To solve these equations, the authors used "a three-stage least square (3SLS) estimator." Again, the 3SLS approach was used because the authors were concerned that a single-equation regression model would not adequately address the "endogenous relationship between dependent variables."

2.1.5 Back Propagation Artificial Neural Network (BPN)

BPN is a form of Artificial Neural Network (ANN). ANNs are designed to mimic the human brain by creating neuron type connections. The benefit of an ANN is that, as more data becomes available, the network has the ability to "learn" to better interpolate values *(18)*.

McFadden et al. (2001) created and compared a PBN with a linear regression model that had been created using the same data set. The study found that the BPN model solved some the collinearity issues. However, it created a model that was very similar to the model created using OLS estimation.

2.1.6 Panel Mixed Order Probit Fractional Split Model

Eluru et al.'s (2013) study was the first time a Panel Mixed Order Probit Fractional Split model (PMPFS) was used for either a transportation or economic application.

2.1.6.1 Montreal 2013

The study used data from 49 collector and 71 arterial road sites from Montreal, Canada. That data was collected using NC-97, 100, and 200 on road sensor devices for a consecutive 7-day period. The authors looked at speed limit, distance to and from an exit, number of lanes, width of lanes and road, sidewalks, parking, bicycle route, quality of pavement, grade of road, horizontal curve, median, and sight distances *(19)*.

A fractional split model was chosen predominantly so that the vehicles could be grouped by speed classes (< 20 km/h, 20-30 km/h, etc.) as opposed to a single speed. The model would then generate probabilities instead of a single speed percentile, such as the 85^{th} or 50^{th}. Like many other authors, Eluru et al. argue that models that produce probabilities result in a better understanding of the road section being studied. Eluru et al. go on to state that the fractional split model also, "explicitly control[s] for vehicle flow conditions (proportion of heavy vehicles) and environmental conditions." To create their model, they used a quasi-likelihood approach. This allowed the authors to set variables which varied from site to site. This was done primarily so that parking could be set as a probability distribution. This model was also able to control for random effects at each site. The authors summarize their model as follows:

> *[…] the current study proposes the ordered response fractional split model. The proposed formulation is further extended to capture the impact of exogenous variables to vary across the population (similar to random coefficients ordered response model) and incorporate the influence of site specific unobserved effects on the proportion variable (similar to a panel random coefficients ordered response model).*

Two separate models were created—one for collectors and one for arterials. The models were estimated using a Panel Ordered Probit Fractional Split Model and a Panel Mixed Probit Fractional Split Model. When the Log-likelihood of convergence of the variables was compared, the Panel Mixed Probit Fractional Split Model was found to be a superior model.

Interestingly, the authors analyzed the speed distributions for different time periods but did not control for free flow condition.

One of the recommendations is to jointly model the roadway volumes and speed proportions, which the authors conclude would be “a significant challenge in terms of modeling.” They also felt that their model, based on the arterial locations, lacked detail and could be “enhanced substantially.”

2.1.7 Model Discussion

In the literature, the primary form of modeling has been the standard Ordinary Least Squares (OLS) technique. As researchers have moved from models with limited representative variables on curves and highways to more complex highway and urban tangent models, the standard OLS estimation has not worked as well. To that end, five other techniques were used to estimate models in the literature most were variations on OLS: linear mixed-effect model (which used the OLS technique for solving), simultaneous equations (which also used OLS), OLS – panel data (OLS-PD), back propagation artificial neural network (BPN), and panel mixed probit fractional split model (PMPFS).

Of the five estimation techniques, only OLS-PD and PMPFS have a wider potential application for tangent operating speed models. McFadden et al. (2001) used the same data set to create two models one using BPN as an estimating technique and the other using OLS. The benefit of the BPN estimation is that it addresses some of the collinearity issues that are of concern in OLS models. However, the BPN technique only produces a single value. This limits the BPN estimation from being able to calculate speed dispersion. Given the 2011 TRC Synthesis Report recommendations that further models have the ability to differentiate between the impacts of speed and speed dispersion, and McFadden et al. (2001) conclusion that the BPN estimation results were very similar to that of the OLS estimation, tangent speed models are not the best application for BPN estimation.

Two models work effectually in their given application but do not extend well to other operating speed models. Himes and Donnell’s study, which looked at the dependency between lanes of traffic, used simultaneous equations and OLS. The simultaneous approach is effective when the goal of the research is to study collinearity of variables but not as well for operating speed models, which are primarily comprised of exogenous variables. Similarly, Wang et al.'s (2006) linear mixed-effects model works well for modeling GPS data that extends across several road sections and the drivers' information is known. This model form would not work well with radar point data. This leaves OLS-PD and PMPFS estimation.

Both the OLS-PD technique and the PMPFS technique address the collinearity issue and meet the recommendations of the 2011 TRC Synthesis Report of being able to "predicting any user-specific percentile, involve more design variables than traditional OLS models, [and] separating the impacts on mean speed from the impacts on speed dispersion". However, of the two estimation types, the PMPFS has been used in to create an urban operating speed model while the OLS-PD technique has only been used to create a highway model.

2.2 Variables

Following is a summary of variables that have been used in urban or tangent models.

2.2.1 Random effects

A random effects variable takes into account variations from site to site and variations within a site, which is not accounted for in model variables. Typically, random effects are accounted for by using error terms. Eluru et al. (2013), Poe and Mason (2000), and Tarris et al. (1996) are examples of different operating speed models that used error terms.

2.2.2 Before and after Curve Data

Before and after curve data are used to predict operating speed on tangents. Typically, this is used on shorter tangent section with minimal access points such as mountainous two-lane highways. Polus et al. (2000) used the before and after curve data for their tangent operating speed model *(12)* and Dell'Acqua et al. (2007) showed that operating speed on a tangent was connected to the speed in the preceding curve *(20)*. The IHSDM also uses curve data for tangents <150ft *(7)*. To avoid the influence of accelerating from or decelerating to a curve, a tangent model generally selects locations that are longer than a minimum value.

2.2.3 Segment Length and Speed Fluctuation Due to Acceleration

Several studies have considered acceleration and speed distribution over tangent sections. He et al. (2010) found that on highways, vehicles typically followed a step response to acceleration (see **Figure 1**). This work was done on highways with an operating speed around 120 km/h. The study found that drivers took on average 700 m to reach the peak speed C_{MAX} *(21)*. On the other extreme, Dinh and Kubota (2013) looked at the speed profile of vehicles on residential streets in Japan with a posted speed limit of 30 km/hr. They found that speed profiles followed a reasonably shallow arc where the max speed was seldom reached right at the midpoint. **Figure 2** outlines a typical speed profile for a section that is 184 m long with most drivers reaching max speed after halfway at around 120 m *(16)*. Most standard arterial and collector roads would fall somewhere between these two extremes.

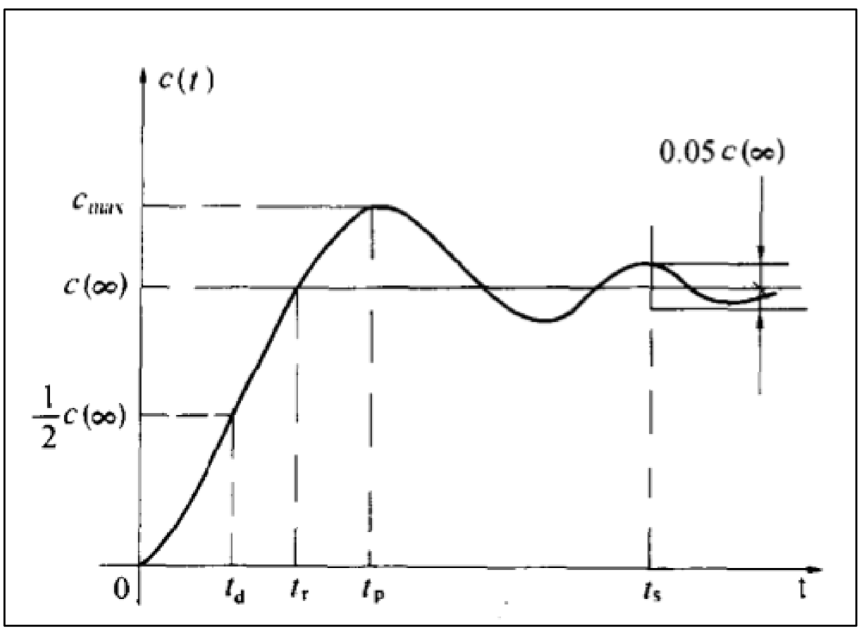


Figure 1 Step response curve *(21)*

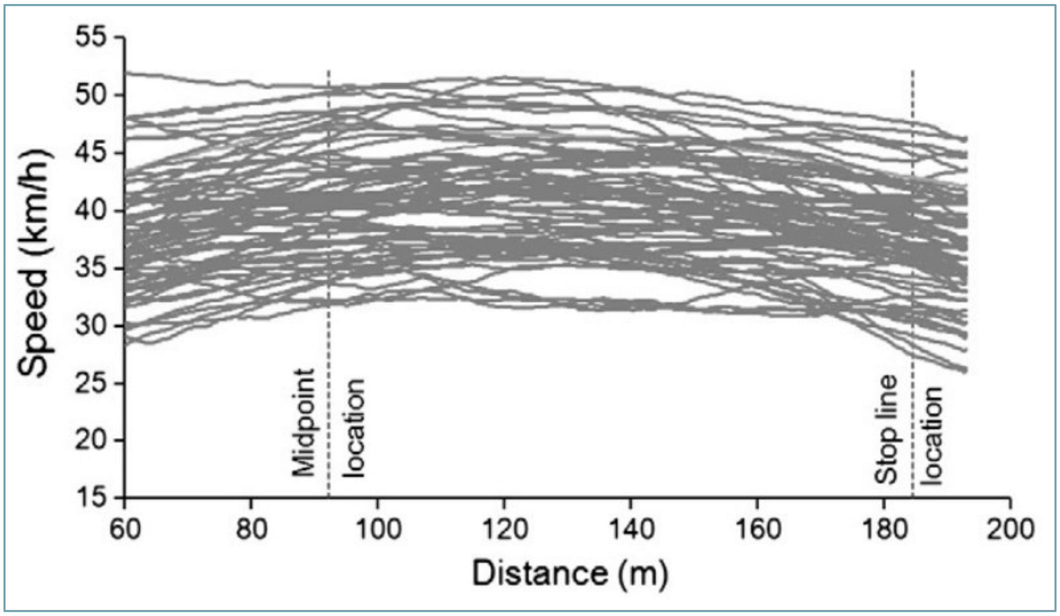


Figure 2 Typical profile speed*(16)*

2.2.4 Carriageway width

Carriageways are typically defined as the usable width of road or asphalt available to vehicles. Undivided roads are considered to be a single carriageway. Divided roads, such as arterials with a median barrier or divided highways with a central median or ditch, are considered dual carriageways. Typically on urban roads, both lane widths and carriageways are measured from the curb face. Therefore, most carriageways would be the sum of the lane widths (this is not the case for highways).

A study by Dihn and Kubota (2013) reviewed carriageways widths along with several other parameters. Their study, which was used for urban roads with 30 km/h speed limits, found that the carriageway width was statistically significant in the choice of operating speed. The carriageways in the study were between 3.40 and 7.10 m with a mean of 5.30 m *(16)*. Japanese streets are significantly narrower than North American roads, where “narrow” residential streets have a carriageway of approximately 8 m.

2.2.5 Medians

Most studies that include a median barrier as a variable indicate that the presence of median barriers increases operating speeds. A study by Fitzpatrick et al. (2001)

reviewed existing operating speed models and found that not only do medians increase driver speeds, but that the type of median (raised versus two-way left turn) had similar affects *(9)*. Fitzpatrick et al.'s (2003) study found that wider medians increased vehicle speeds *(22)*. Himes and Donnell (2010) had slightly different findings: they found that two-way left-turn lanes did not affect the mean speed but did reduce speed variation in the left lane *(23)*.

In their Calgary study, Tay and Churchill (2007) went into more depth, focusing on the effect of different barrier styles on median lane traffic for four lane roads. They looked at six types of barriers: ditch, curb, w-beam, thrie-beam, f-barrier (Jersey-barrier), and f-barrier with chain-link fence. They studied two sections of road, one with an 80 km/h posted speed limit and the other with 70 km/h posted speed limit. The 80 km/h road had each of the barrier types, while the 70 km/h road only had raised curb, w-beam, and f-barrier. All of the studied road sections were tangents with similar geometric features. Interestingly, the f-barrier on both road types had the highest observed operating speeds followed by the w-beam, wide ditch, and then raised curb. For the F-barrier, the 85th percentile operating speed was 23 km/h higher than the posted speed limit of 80 km/h and 10 km/h higher than the 70 km/h speed limit *(24)*.

Tay and Churchill's (2007) findings conflicted with the Highway Capacity Manual's (HCM) recommendations. The HCM states that drivers will reduce their free flow speeds based on the lateral clearance values, and provides tables for this adjustment. Tay and Churchill's studies oppose the latter, namely because F-barriers adjacent to the travel lane had the largest speed increases.

2.2.6 Sidewalks/ Pedestrian Activity

Sidewalks can be viewed from two perspectives. If the walk is monolithic with a curb and gutter, it could increase the driver's perceived clear zone. Alternatively, sidewalks can act as proxy for pedestrian activity. Such a varied perception of sidewalks is also represented in the literature. In their study of 30 km/h residential roads, Dihn and Kubota (2013) found a strong positive correlation between operating speed and the presence of a sidewalk *(16)*. Eluru et al. (2013) also found a similar increase in operating speeds where sidewalks were present *(19)*. On the other hand, Wang et al.

(2006) found a strong negative correlation between sidewalks and operating speed *(15)*. None of these studies differentiated between monolithic and boulevard walks.

However, when Fitzpatrick et al. (2003) explicitly looked at the impact of pedestrian activity, they found that operating speed decreases with an increase in pedestrians *(22)*.

2.2.7 Roadside object density/ Clear Zone/ Roadside Hazard

The two main ways to calculate the magnitude of the hazard if a vehicle leaves the road include roadside object density and size of clear zone. Urban models tend to use roadside object density variable whereas highway models use clear zones. This difference likely relates back to the design of these facilities as arterials and collectors typically have curb and gutter with a minimum offsets for objects (usually around 1.5 m). Highways, on the other hand, often have a recovery zone or a clear zone requirement. The IHSDM combines these two approaches and assigns a Roadside Hazard Rating (*RHR*) value of one to seven. Determining the *RHR* value takes into account a measurement component and a visual assessment component. The online report FHWA-RD-99-207 **appendix D** includes descriptions and examples of each rating classification *(7, 25)*.

Regarding roadside objects, there is a clear reduction in speed based on density. Dihn and Kubota (2013) observed this relationship in their study of 30 km/h residential roads *(16)* as well as by Wange et al. (2006) *(15)*.

Clear zones have a similar impact on drivers' speed choice. As the clear zone increases, drivers choose a higher speed. Himes and Donnell (2010) used a binary operator to indicate the presence of a 20 ft clear zone. They found that if there were 20 or more feet of clear zone, there was an increase in operator speeds *(23)*.

In one study, Fitzpatrick et al. (2003) controlled for clear zone and looked specifically at shoulder widths. The study found that, "no distinct relationship exists between shoulder width and operating speed […]" *(22)*.

2.2.8 Access Density

Access density is the number of residential and business driveways or access points per meter or per kilometer. Throughout the literature, there is a strong sense of agreement that an increase in driveways or access decreases overall operating speed. For example, see the studies by Wange et al. (2006) and Figueroa et al. (2005) *(15, 17)*. Interestingly, Himes and Donnell (2003) and Fitzpartick et al. (2010) discovered that, for four lane roads, access density largely only impacted the right lane speeds *(22, 23)*.

2.2.9 Pavement Quality

All studies that explored pavement quality have indicated that good, smooth pavement has a positive impact on drivers' speeds *(19)*.

2.2.10 One-way

Eluru et al. (2013) found that vehicles on a one-way road travel slower than in similar conditions on a two-way road *(19)*.

2.2.11 Curb and gutter

Operating speed and the existence of a curb and gutter have no clear relationship. The two studies that looked at curb and gutter resulted in different findings. Fitzpatrick et al. (2003) found that curb and gutter did not have an impact on speed choice, whereas Wang et al. (2006) found a strong positive correlation between the existence of a curb and operating speed *(15, 26)*. These findings were strongly influenced by the type of road sections chosen, where curb and gutter were not a major defining feature but, rather, a proxy.

2.2.12 Right safety strip width

In their study on 30 km/h residential roads, Dihn and Kubota (2013) determined a medium positive correlation between operating speed and the width of the right safety strip *(16)*.

2.2.13 Road Markings

Fitzpatrick et al. (2003) found that the absence of centerline and edge markings correlates to reduced speeds *(22)*.

2.2.14 Lane Impacts

The impact of lanes has been studied using various approaches.

Himes and Donnell (2010) studied the impacts of traffic flow, in the same direction, in two different lanes. They found a positive correlation between the speed of traffic in one lane and the speed of traffic in the other. There was also a correlation between increased speed variability and lower mean speed both in a given lane and as between lanes *(23)*.

Eluru et al. (2013) and Wang et al. (2006) looked at the impact of total number of lanes on driving speeds. They both found that operating speeds increased as the number of lanes increased *(15, 19)*.

Surprisingly, many of the disagreements reflected in the literature originated from studies that solely examined lane widths. Fitzpatrick et al. (2003) did not find any correlation between lane widths and speed *(22)*. Conversely, Dell'Acqua et al. (2007) found a positive correlation between lane width and speed. The study was performed in Italy, where many of the roads do not meet a North American geometric standard *(20)*. Poe and Mason (2000) also found that lane width has a statistically significant impact on speed, but their study was on curves rather than tangent sections *(27)*.

2.2.15 Bike route

Eluru et al.'s (2013) study, found that driver drove faster on routes with bike lanes. The authors argued that this is attributed to the type of roads bicycle routes are installed on as opposed to drivers speeding up because of a marked bicycle route *(19)*.

2.2.16 On Street Parking

For one of two reasons, research demonstrates that on street parking has a statistically significant impact on reducing operating speeds. First, a road cross section with parking has a more constructed "feel" with less clear zone. Second, vehicles pulling in and out of parking spaces have an impact on through traffic. It may be difficult to determine which of these two potential aspects is responsible for the speed reduction in a given road segment.

Eluru et al. (2013) conducted a study on the impact of parking. They did not explicitly state which aspect they were primarily focusing on. However, from their model, it seems that they concentrated on the act of parking versus the effects of the stationary parked vehicles. In particular, they considered "parking" as a normally distributed variable, but they did not discuss the level of occupancy of the parking facilities *(19)*. Whether or not it is a reasonable assumption, to assign parking a normal distribution, Fitzpatrick et al. (2003) and Wang et al. (2006) found the same negative impact of parking on operating speeds *(15, 22)*.

2.2.17 Sight distance and Length of Tangent Section

Several studies have found that longer sight distances (stopping sight distance) strongly influence the speed that drivers choose. Tarris et al. (2000) looked at six sites in Pennsylvania, USA, which had sight distances varying from 0.29 km to 1.55 km in length. They collected speed data at several points along these corridors. They found that operating speed was highly correlated to stopping site distance *(28)*. Figueroa et al. (2005) had similar findings when they looked at sight distance *(17)*.

Tangent length is sometimes used as a proxy for sight distance with similar results. In their study of 30 km/h residential roads, Dihn and Kubota (2013) determined that operating speeds reduced as the tangent lengths got shorter *(16)*. Similarly, Dell'Acqua et al. (2007) found that the speed of vehicles in Italy were dependent upon the length of the tangent *(20)*.

2.2.18 Width ratio of crossing Street and Study Street

In their study of 30 km/h residential roads, Dihn and Kubota (2013) found a strong negative correlation between operating speed and the width ratio of crossing street and study street *(16)*.

2.2.19 Impact of Intersections

Increased intersection density has an overall effect of lowering operating speed. Himes and Donnell (2010) found that not only did overall mean speeds reduce with the density of intersection, but that the density of intersections had a more pronounced effect on right lane traffic *(23)*. Fitzpatrick et al. (2003) used the term "signal density" and had similar findings *(22)*. Wange et al. (2006) showed that T-intersections have a similar impact on operating speeds *(15)*.

2.2.20 Land Use

The type of land use around roads has an impact on operating speeds. That said, different studies report different findings. Both Himes and Donnell (2010) and Wang et al. (2006) realized that commercial areas had the biggest impact on reducing operating speeds. Himes and Donnell looked at the impact of commercial, wooded, and residential land use. They found that commercial land use had the lowest right lane speeds. Wang et al. determined that operating speeds were 3.3 mph (5 km/h) slower in commercial areas than any other. They argued that this was due to the higher number of distractions and turning movements in commercial areas *(15, 23)*. On the other hand, Fitzpatrick et al. (2003) found that residential zones had the largest impact on lowering operating speeds *(22)*.

2.2.21 Truck Traffic

Another variable for which studies have had mixed results is heavy truck traffic. Himes and Donnell (2010) found an increase in right lane speeds with an increase in heavy traffic *(23)*. Conversely, Figueroa, Medina and Tarko (2013) determined that speeds were reduced proportionately to the percentage of trucks in the traffic *(17)*.

2.2.22 Posted Speed Limit

Early operating speed model authors often disagreed on whether the posted speed limit should be included as a variable. At one extreme, Fitzpatrick et al. (2005) conducted a study on 79 suburban and urban roadway sections across seven states and found that the most statistically significant indicator of operating speed is posted speed limit. The authors extended this finding to create operating speed models that only included posted speed limit *(13)*. On the other extreme, Wang et al. (2006) argued that "[b]cause the design speed is generally based on the proposed speed limit, road characteristics (particularly geometric elements) are highly correlated to the speed limit." Accordingly, they did not include posted speed limits in their model *(15)*.

Other authors, like Eluru et al. (2013), had mixed results, finding that while speed limit has an impact on the speed people chose to drive, the amount of effect varied from location to location*(19)*. Dinh and Kobota (2013) tried to control for speed limits by creating different models for each speed limit. They concluded, "If a study is to reveal the influence of street characteristics outside of speed limits on drivers' speed choice, it would be better to develop speed models based on single speed-limits" *(16)*.

Himes and Donnell (2013) resolved the issue by conducting an in-depth study on whether or not speed limits should be in operating speed models. They concluded that posted speed limits should be included in models because, if they are excluded, the impacts of geometry on operating speed can be exaggerated. They also found that posted speed limits can simply be included as an exogenous variable *(11)*.

2.2.23 Speed Distribution

Chung and Recker (2014) argue that speed dispersion is crucial for understanding traffic flow. Speed dispersion or distribution plays a role in traffic safety, value pricing, operating efficiency, air emissions, and energy consumption *(29)*.

Himes and Donnell (2010) were the only authors to explicitly look at speed dispersion in conjunction with their operating speed model. They found that, as the mean speed of traffic increased, the speed deviation within the flow decreased *(23)*. Figueroa et al. (2005) used an OLS-PD estimation which allowed for the model to indicate speed distributions but did not study the impact of the speed distribution *(17)*. Similarly, Eluru et al. (2013) used a PMPFS estimation, which could be used to determine the speed distribution. However, the speed distribution was not included as part of the study *(19)*. The 2011 TRB Synthesis Report recommends that future models be able to, "distinguish mean speed factors from speed dispersion factors" *(7)*.

2.2.24 Temporal variation and variability of speed in flow

Variations of traffic flow, due to changing road conditions such as weather or time of day, have typically been controlled for and removed from the data set. When elements such as time of day were studied, it was found that operating speed did vary *(19)*.

The 2011 synthesis report recommended that further research be conducted on modeling nighttime speeds as nighttime collisions and severity are over-represented and that, “operating speed-design consistency may be a more important consideration at night than during the day” *(7)*.

2.2.25 Variables Discussion

Following is a summary of the major variables studied in operating speed models.

Sight distance and length of tangent have clear positive impact on operating speed. Intersection density also has a clear impact on operating speed but for the negative.

Land use has a less clear, yet statistically significant, impact. The studies that examined land use show an impact but have mixed results. This could partially be due to the fact that land use acts as a proxy for other road features, such as number of turning movements or access density, and could be highly impacted by local design guidelines.

The center of road treatment has a statistically significant impact on operating speeds. The absence of road markings generally has a reducing effect on traffic speeds. If several studies are linked together, it is commonly inferred that as median treatments become more robust, speed increases roughly in the order of the treatment: no line, painted line, painted median, two-way left turn lane, raised concrete median, barrier, and ditch.

Variables that quantify side access, the offset of roadside objects, and density of roadside objects have a statistically significant impact on drivers’ speed. Examples of this include access density, driveway density, roadside object density, clear zone, and roadside hazard rating. Parking is a mix of both access and roadside objects and also has an impact on drivers’ speeds.

Pavement quality has been shown to impact driving speeds. However, it is difficult to include pavement quality in models for the northern part of central North America or the East coast of North America due to the winter conditions, predominantly freeze and thaw cycles, which can significantly shift the road surface quality over a relatively short period of time. This makes pavement quality a less static variable than other parts of North America.

Road width has been primarily measured in two ways: lane width and carriageway width. The correlation between lane widths and operating speed is unclear. However, studies have shown that wider carriageways tend to increase operating speeds.

Several variables have either had mixed results or have not been studied adequately. One variable with mixed results is sidewalks. The majority of studies indicate that sidewalks have a positive impact on drivers' speed. The difficulty is that no studies differentiated between monolithic and boulevard walks, which could explain some of the conflicting results. Another variable with mixed results is percentage of trucks. This may be due to trucks in urban settings having very different speed profile than trucks on highways.

Road grade is a statistically significant variable but is typically not included in studies. Finally, one study that analyzed bike routes showed that they increase operating speed. However, no study has looked at the impact of different types of bike routes on operating speed.

2.3 Summary

This literature review has identified several gaps in urban operating speed models. First, there are very few urban tangent models, especially models which have a significant number of geometric variables. One of the issues with models that include a lot of variables is collinearity between variables. One option to reduce collinearity is to use panel data. Currently, the only model that has used panel data ordinary least squares (OLS-PD) technique is for highways.

Several variables have either not been included in most models or, where they are included, their impact was inconclusive. One such variable is sidewalks. All models that have involved sidewalks included it as a binary operator. This could partially explain why sidewalk variables have such mixed results. Drivers would perceive a curb and gutter with monolithic differently than a boulevard walk that is behind trees and other fixed objects.

Another road attribute that has not been explored is how different types of fixed objects affect drivers' speeds. Recent studies examined roadside hazards, but only in mass. Typically, this is in the form of clear zone, density of objects, or a numeric roadside hazards rating. Limited studies examined the difference between a road with streetlights and fire hydrants, as opposed to an equal number of mature trees.

Road grade and bike routes have been included in very few studies. In the instance that bike routes were included, there was no indication of the type of facility. There is a significant difference between a buffered bike lane and a shared-use lane.

With regards to outputs, most operating speed models produce a single value, usually the 85^{th} percentile speed. This does not help in differentiating the impacts of speed versus speed dispersion. Two estimation techniques, OLS-PD and PMPFS, output speeds for all percentiles or vice versa, allowing for the relationship between speed and speed dispersion to be studied.

3 Research Methodology

The literature review showed that, on divided highways, there are generally few variables other than road geometry and posted speed limit that influence a driver's operating speed. This is not surprising since highways usually follow a uniform design guideline and have controlled access points. As the road type changes from divided highways to two lane divided highways to arterials and into the urban environment, more variables became statistically significant. Numerous features, from land use to pavement quality, have been studied and found to impact operating speed. This study extends the findings discussed in the literature review by using a larger speed data set and significantly more variables including categorical variables. This study also used speed percentiles, panel data, and speed distribution to further study the impact of given attributes on drivers operating speeds.

3.1 Data

The data set assessed in this study was previously collected by the City of Edmonton Office of Traffic Safety in a major field survey of approximately 600 locations over four years. The data was then refined on a preliminary basis by eliminating all non-free flow traffic data and all non-tangent sections.

Additional data attributes were added to the refined data. In additional, for each location percentiles based on speed and their corresponding *Z* values were added.

3.1.1 Base Data

The City of Edmonton collected the base data set between 2009 and 2013 using a Vaisala Nu-Metrics Portable Traffic Analyzer NC200 (see **Appendix C**). The sensor is place on the road and measures speed, number, and length of vehicle. Data was collected at 596 locations.

3.1.2 Base Data refinement and Additional Data

Prior to this study, the base data was refined to include only free flow traffic with a two second headway. For a discussion on why two seconds was used, see Gargoum et al.'s (2015) paper, "Factors Influencing Drivers Compliance to Speed Limits on Urban Roads." *(30)*

Second, all non-tangent locations and residential roads were removed from the 596 base locations. Of the original 596 locations, 316 were removed, leaving 280 locations. Of the remaining 280 locations, 126 were arterial, 123 were collector, and 31 were classified as 'other' (typically major residential roads that were close in functionality and had similar properties to a collector road). For this study, additionally data were added or computed for the remaining 280 locations. The four categories of new or computed data include general road features, roadside features, on road features, and traffic flow.

3.1.2.1 General road features

Five general road features that were added to the data: the entry and exit features of the tangent section, the length of the tangent section, whether the road is a one-way, the presence of a pedestrian crossing, the type of land use, and the posted speed limit.

3.1.2.1.1 End treatment of tangent section

Tangent sections are generally defined as straight road sections between intersections or curves. For each tangent segment assessed in this study, two boundary conditions or end treatments (one at either end, bookending the tangent section) were defined. The four end conditions observed in the data locations are: signalized intersection (labeled 1), stop controlled intersection (labeled 2), curve (labeled 3), and intersection with right of way (labeled 4).

For this study, curves (condition number 3) are one of the possible end treatments within the general road features category. This is in contrast to several studies of highway tangent sections that found that the degree of curve at ends of tangent sections influences speeds on tangents (see section 2.2.2). However, on urban arterials and collectors in the data set, there were significantly more intersections as boundary conditions than curves. Based on this, a 'curve' was used as a categorical end treatment as opposed to a separate numerical value.

Treatment number 4 (intersection with right of way) was the intersection type where the vehicles on the tangent had no stop or yield control.

3.1.2.1.2 Length

The length of the tangent section was measured (in meters) from the center of an intersection or the beginning of a curve.

3.1.2.1.3 One-way

Whether a road was a one-way or not was recorded as a binary operator.

3.1.2.1.4 Midblock Pedestrian Crossing

Initially, all types of midblock pedestrian crossings were recorded: pedestrian actuated signal, pedestrian actuated flashers, and painted crossing. However, when this level of detail was modeled, it was discovered that there was no statistically significant impact on vehicle speeds between the types of crossing. In order to determine the overall impact of pedestrian crossings on operating speeds, all crossings types were grouped into a single binary operator.

3.1.2.1.5 Posted Speed Limit

The posted speed limit was included in kilometers per hour.

3.1.2.2 Roadside features

Roadside features include nine elements of the built environment directly adjacent to the tangent section. These nine elements indicate how many structures there are and how close they are to the road, how much access there is for vehicles, the presence and type of sidewalk, and whether there is a bus stop.

3.1.2.2.1 Roadside treatment

Roadside treatment was broken into four categories: downtown commercial, mixed high to medium density, mixed low density, and open urban. These ratings are intended to classify the general offset of buildings from the road and the intensity of uses directly adjacent to the road. These classifications are meant to act as a generalized proxy for visual distractions and intensity of pedestrian traffic.

3.1.2.2.1.1 Roadside treatment - Downtown Commercial

Downtown commercial represents the highest density of buildings and the least amount of offset from the road. Buildings typically front directly onto the sidewalk with the area between the road and building being hardscaped with some trees and street furniture. The offset of the buildings from the road is typically 2 to 5 meters. Downtown Commercial was assigned a value of 1.

Table 1 Downtown roadside treatment

Jasper Avenue at 105 Street


Whyte Avenue at 105 Street

3.1.2.2.1.2 Roadside treatment - Mixed High to Medium Density

Commercial and residential mixed use buildings are offset from the road by 5 to 8 meters. Buildings are typically over three stories. The area between the building and the road usually has some landscaping either as a boulevard area with or without trees, or a landscaped area between a monolithic sidewalk and building. Mixed High to Medium Density was assigned a value of 2.

Table 2 Mixed high to medium density roadside treatment

100 Avenue at 105 Street

3.1.2.2.1.3 Roadside treatment - Mixed Medium to Low Density

Mixed low density represents lower pedestrian use with offsets between 8 to 18 meters. Typically, these areas have sidewalks with larger frontages. The Mixed Low Density category includes most residential collectors, roads with three story residential walk ups, light industrial areas with small front parking lots, and lower density strip malls that have controlled access. Mixed Low Density was assigned a value of 3.

Table 3 Mixed medium to low density roadside treatment

116 Street at 107 Avenue: Collector with medium density residential (typical three story residential walk up buildings)

116 Street at 109 Avenue: Collector with low density residential

3.1.2.2.1.4 Roadside treatment - Open Urban

Open Urban is the lowest urban density around the road. This includes arterials that are paralleled by noise berms or noise walls, which offer minimal visual distraction. Often there are no sidewalks or, where walks are present, they have a significant offset from the road. This classification also includes commercial and industrial areas with large parking lots or other large features that significantly increase the offset of buildings from the road. Open Urban was assigned a value of 4.

Table 4 Open urban roadside treatment

 170 Street at 97 Avenue	 170 Street at 99 Avenue

3.1.2.2.2 Sidewalks

Sidewalks were divided into four categories: boulevard walk on both sides of the road (assigned a value of 1), boulevard walk on one side and mono walk on the other (assigned a value of 2), mono walk on both sides (assigned a value of 3), and no walk or boulevard on one side (assigned the value of 4). It was found that most roads had at least one sidewalk.

3.1.2.2.3 Bus Stop

The presence of a bus stop on one or both sides of the road was noted as a binary operator. If a bus stop was present, this variable was assigned a value of one.

3.1.2.2.4 Boulevard Width

The boulevard width was recorded in meters and it was averaged between the two sides. Boulevard width was noted as zero for any location that did not have a boulevard walk, including all mono walks.

3.1.2.2.5 Number of accesses per Kilometer

All driveways, commercial accesses, and alley accesses were counted and recorded. The total number of accesses was divided by the length of the road section in kilometers. This variable could also be referred to as access density.

3.1.2.2.6 Pole Density per Kilometer

All streetlight, utility, trolley, and power poles on both sides of the road were also counted and recorded. The total number of poles was divided by the road length in kilometers. This count did not include signage poles, such as stop signs or street blade poles, or trees.

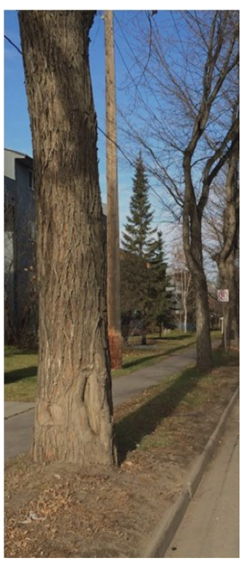
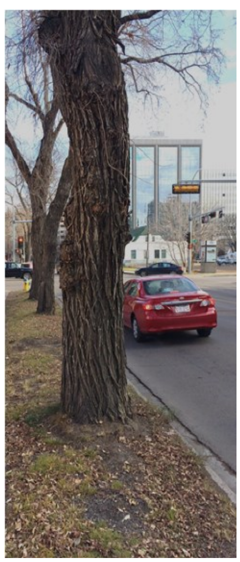
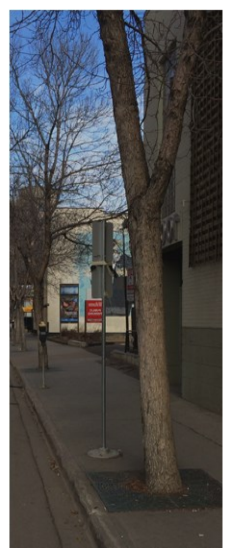
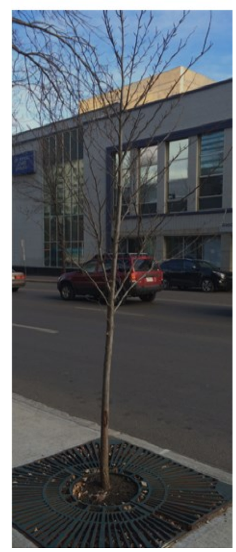
3.1.2.2.7 Tree Density per Kilometer

The total number of trees on both sides of the road was divided by the total length of road in kilometers.

3.1.2.2.8 Tree Maturity

Tree maturity was classified into three groups. Group 1 included mature trees on one side or both. Group 2 comprised mixed tree age on one side, young trees on one side, and midsized or mixed on the other side, or midsized trees on both sides. Group 3 involved no trees, young trees on one side, or young trees on both sides.

Table 5 Example of tree sizes for tree maturity variable

 	 	
Mature Trees	Midsize Trees	Young Tree

3.1.2.2.9 Average Object Offset

Average object offset is the average distance of all trees and poles from the face of curb. The maximum offset was 10 meters. Where there were no obstructions, such as an open field or parking lot, a value of 10 meters was assigned.

3.1.2.3 On road features

As part of the study, seven on road features were documented: median type, road width, number of lanes, curbside parking, road grades, on road bike markings, and the presence of a service road. Of the seven attributes recorded, only road grade was removed before modeling as the majority of tangent sections were essentially flat.

3.1.2.3.1 Median

The median was divided into six categories: no line (assigned 6), painted line (assigned 5), painted median or shared center turning lane (assigned 4), raised median with or without trees (assigned 3), all types of barrier medians (assigned 2), and divided median (assigned 1).

3.1.2.3.2 Road Width

In this study, road width measures the asphalt width of the roadway. Where there was either no centerline or a painted centerline, road width was measured from curb face to curb face. Where the center of the road was a painted median or raised median, the two carriageways were measured from curb face to the edge of the median, either a curb face or painted line. In the case of a center ditch with no curb face, the carriageway was measured from curb face to edge of pavement. In the case of a barrier median, the carriageways were measured from curb face to barrier face. In all cases, the road width was both carriageways added together. Road width was recorded in meters.

3.1.2.3.3 Number of Lanes

Number of lanes was defined as the total number of travel lanes. Defined parking lanes were not counted as a lane but rather were included in the road width value and on street parking was noted.

3.1.2.3.4 Curbside Parking

Roadside parking was defined in three categories: no parking, off peak parking, and parking. No parking was only used for roads which had 'no parking' signs on both sides of the road (assigned 3). Off peak parking was use where either side of the road banned parking during peak hours (assigned 2). Finally, all locations that allowed parking including meters (assigned 1).

3.1.2.3.5 Road Grades (not used)

The percent of road grades were initially recorded. However, once all study locations were reviewed, it was found that few locations exceeded the standard grades required for drainage. Therefore, road grades were not included in the models.

3.1.2.3.6 On Road Bike Markings

On road bike markings were broken into five categories. One category included no bike marking and sharrows on one side or both (assigned 5). The next category was a marked bike lane on one side of the road (assigned 4) followed by a marked bike lane on both sides of the road (assigned 3). The last two categories were a marked bike lane on one side and a buffered bike lane on the other (assigned 2) and buffered bike lanes on both sides of the road (assigned 1). Initially, sharrows and no bike lanes were separate categories. However, in early iterations of the model, sharrows were found to have no impact on drivers speed thus they were combined with no markings.

3.1.2.3.7 Service Road

A service road is a road directly adjacent to a higher volume road, typically an arterial, which is used for local access. This study notes the presence of a service road on one or both side of the road as a single binary value.

Table 6 Service roads

111 Avenue at 116 Street: divided arterial with service road on both sides

127 Street at 119 Avenue: undivided arterial with single service road

3.1.2.4 Traffic Flow

Two attributes of traffic flow were recorded: vehicle speed and average vehicle length.

3.1.2.4.1 Vehicle Speed

The base data included the speed of individual vehicles in kilometers per hour. The fact that the speeds were not aggregated together allowed for this study to determine Speed Distribution from the speed data.

3.1.2.4.2 Average Vehicle Length

The average vehicle length was used as a proxy for the percent of traffic flow that was trucks.

3.2 Model

Medina and Tarko (2005) used ordinary-least-squares panel data (OLS-PD) to estimate their model. The OLS-PD estimation was chosen for three reasons: OLS estimation has been shown to work well with operating speed models, PD allows for more than a single percentile speed to be used, and PD allows for the consideration of variability in speeds *(17)*.

Of the operating speed models reviewed in the literature, all but one used OLS for estimation. OLS estimation is a good fit for operating speed models as the data is typically exogenous to the model. An OLS estimation minimizes the difference between data points and has the form:

$$V_i = \sum_k b_k X_{ik} + \varepsilon \qquad [9]$$

where

V_i = the speed of a given percentile at location *i*

b_k = the coefficient for variable *k*

X_{ik} = the value of variable *k* at location *i*

ε = the error term

There are two main drawbacks to OLS estimation. First, the estimation performs poorly if the variables are correlated. Collinearity between variables can be mitigated by testing for it and by using PD. PD reduces multicollinearity by increasing the number of observations and degrees of freedom.

The second limitation to models developed using OLS is that each observation can only incorporate one response variable. OLS- PD overcomes this by using PD. The PD is arrayed in percentiles from the 5^{th} percentile to the 95^{th} percentile. Traffic speeds follow a normal distribution *(31)*, which means each percentile also has a correlating normal distribution *Z*-value. For instance, the Z_{50} or the *Z* value corresponding to the 50th percentile speed (V_{50}) is zero. The Z_{85} which corresponds to the standardly used V_{85}, is 1.036. This allows for each location to be broken into 19 data points. The PD also factors speed variation into the model. The first component of the equation is then the mean speed at location *(m_i),* while the second incorporates the speed variability. The speed variability is incorporated by multiplying the *Z*-value for the given percentile (Z_p) by the standards deviation (σ_i) for a given speed.

$$V_{ip} = m_i + Z_p \times \sigma_i + \varepsilon = \sum_j a_j \times X_{ij} + \sum_k b_k \times (Z_p \times X_{ik}) + \varepsilon \qquad [10]$$

where

V_{ip} = the speed of a given percentile at location *i*

m_i = the mean speed at location *i*

Z_p = the *Z*-score associated with the given percentile *p*

σ_i = the standard deviation of individual speed *i*

ε = the error term

a_j = the coefficient for variable *j*

X_{ij} = the value of variable *j* at location *i*

b_k = the coefficient for variable *k*

X_{ik} = the value of variable *k* at location *i*

In the above model, the $\sum_j a_j \times X_{ij}$ portion of the equation is similar to a model using the standard OLS technique, where the a_j term is the coefficient associated with a given parameter. The $\sum_k b_k \times (Z_p \times X_{ik})$ portion is more unique as it models the variability in the operating speeds.

3.2.1 Multicollinearity

Multicollinearity was investigated using several approaches. First, variables that were clearly correlated were combined or one was dropped. For instance, Road Side Hazard Rating (*RHR*) and average object offset are correlated as they both measure the clear space at the side of the road. Thus, only average object offset was used in the model. The combination of variables was more typical with categorical variables, where there was no apparent difference in result between categories. Finally, the linear relationship between all variables was tested using SAS's Correlation Analysis (PROC CORR). No statistically significant correlation was found between the variables.

3.2.2 Panel Data

Traditionally, panel data is used in medical and economic research. The use of panel data in this thesis differs from traditional panel data use in two ways. First, panel data is typically spread across time where every observation represents a different month, year, decade etc. In this study the panel represents speed percentiles rather than time. Second, panel data is typically laid out with the time across the top. In the typical panel data set each column represents a different time. This study transposes that and rows become the panel data with each row representing a different speed percentile for each location.

3.2.3 SAS Modeling

The data was modeled using Statistical Analysis System (SAS). The General Linear Model (GLM) procedure was used. The GLM is similar to the more common regression procedure (REG). Both models "[fit] least-squares estimates to linear regression models" *(32)*. The main difference between the GLM procedure and the REG procedure is that the GLM can model class or categorical variables.

3.2.4 Model Refinement

The model followed a stepwise backwards elimination process, wherein the variables with the least significance were eliminated first. The model was rerun every time a variable was eliminated. The model followed this iterative process until all variables had a significance of 99% or higher. See **Figure 3** for the process that was followed.

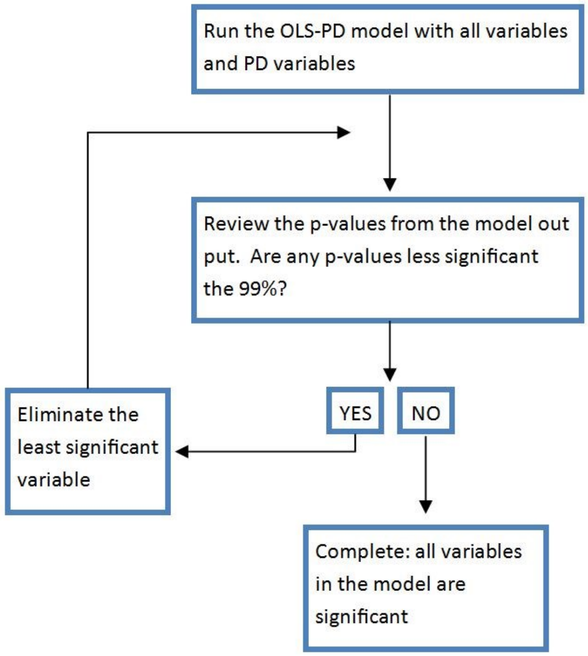


Figure 3 Stepwise procedure - backwards elimination

The stepwise backward elimination procedure was run four separate times. The locations were modeled by road classification. The first model was run for the entire data set, then the collector and arterial location, and finally for the collector and arterial locations, separately. The number of iterations required for the four separate models varied from 15 to 29 iterations.

3.2.5 Goodness of Fit

The goodness of fit was tested using the R-squared test. The goodness of fit results are shown in **Table 11** and **12**. The R-squared test is a unit less ratio between 0 and 1, where 1 is a perfect fit. All four models have a good fit as there R-squared value is greater than 0.60.

3.2.6 Final Models

Four models were created using the data set. The first model used the data for all 280 locations comprising 5,320 data points. This data included arterial, collector, and some residential, which acted like minor collectors. The second model included only the roads that were classified as arterial and collector (A&C). The A&C model was based on 249 locations and 4,731 data points. The third model was arterial roads only, comprising 126 location and 2,394 data points. The fourth and final model was collector roads only. The collector model was based on 123 locations and 2,337 data points. All four models are in **Appendix A**. Following are a summary table of the four models, statistical summary of continuous variables, a summary table for the class variables and a summary table for the binary variables.

Table 7 Model data summary

Model Name	Model Abbreviation	Number of Locations	Number of Data Points	Number of Statistically Significant Variables Relating to:	
				Speed	Speed Variability
All Data	All	280	5320	11	3
Arterial and collector	A&C	249	4731	12	4
Arterial	A	126	2394	13	3
Collector	C	123	2337	15	2
Starting number of variables				*23*	*23*

Table 8 Statistical summary of continuous variables

Variables	Units	Min	Max	Average	Mean	Standard Deviation
Median Width	meters	0	104	2.57	0	7.36
Length of Road	meters	43	1363	216	173	177
Width	meters	7	56.8	14.5	12.4	5.4
Number of Lanes	number	1	7	3	2	1.3
Total Blvd	meters	0	15.8	2.5	1.1	3
Access Density	number per km	0	141	18	11	20.8
Pole Density	number per km	0	115	33	27	16.6
Tree Density	number per km	0	203	82	85	50.6
Avg Offset	meters	0.5	8.9	3.0	3.0	1.7
Posted Speed Limit	km / h	40	100	53.3	50	6.6
Avg Veh Length	number per km	4.3	8.3	5.4	5.3	0.39

Table 9 Summary of class variables

Variables	Variables	Number of Locations
Median Type	1 - Divided median 2 - All types of barrier medians 3 - Raised median with or without trees 4 - Painted median or shared center turning lane 5 - Painted line 6 - No center markings or median	1 - 10 2 - 1 3 - 70 4 - 10 5 - 84 6 - 105
NEEnd	1 - Signalized intersection 2 - Stop Controlled 3 - Curve 4 - Intersection with right of way	1 - 79 2 - 16 3 - 20 4 - 165
SWEnd	1 - Signalized intersection 2 - Stop controled 3 - Curve 4 - Intersection with right of way	1 - 77 2 - 24 3 - 15 4 - 164
Roadside	1 - Downtown commercial 2 - Mixed high to medium density 3 - Mixed medium to low density 4 - Open urban	1 - 13 2 - 19 3 - 176 4 - 72
Parking	1 - Parking allowed 2 - Off peak parking 3 - No parking	1 - 164 2 - 3 3 - 113
Walk	1 - Boulevard walk on both sides 2 - Boulevard walk on one side, mono walk on other side 3 - mono walk on both sides 4 - Boulevard walk on one side or no walk	1 - 76 2 - 49 3 - 84 4 - 71
Tree Maturity	1 - Mature trees on one or both sides 2 - mixed ages of trees on one or both sides 3 - Young trees on one or both sides	1 - 150 2 - 70 3 - 60
Road Class	A - Arterial C - Collector L - Local/ Residential	A - 126 C - 123 R - 31
Bike Route	1 - Buffered bike lanes 2 - Marked on one sides, buffered on other side 3 - Marked bike lanes on both sides of road 4 - Marked bike lane on one side 5 - No marked bike lanes or sharrows	1 - 2 2 - 1 3 - 9 4 - 1 5 - 267

Table 10 Summary of binary variables

One-way	0 - 273 1 - 7
Midblock Ped X-ing	0 - 266 1 - 14
Bus Stop	0 - 139 1 - 141
Service Road	0 - 246 1 - 34

The data was equally split between arterials and collectors, each having 126 and 123 locations respectively. Also, the most number of statistically significant variables is when the arterial and collector data sets are combined. Interestingly, the A&C model is not simply the addition of all the statistically significant variables in the A and C models. Median type, the conditions at the ends of the tangents, parking, length, and type of walk are all statistically significant in the A&C model but not the A or C models. Statistically significant variables will be discussed further in the findings section.

Another observation is that there are significantly more variables that affect speed than speed variability. This occurs at a ratio of around three or four times more speed variables than speed variability variables.

4 Modelling Results and Discussion

Following is a comparison of the four models and a discussion on each of the statistically significant variables in turn. **Table 11** summarizes the speed variables that are statistically significant in the models. **Table 12** summarizes the speed variability variables that are statistically significant. In **Table 11** and **12**, "Yes" notes a categorical variable which is statistically significant.

Table 11 Variables which influence operation speed

Variables	All Model	A&C Model	Arterial Model	Collector Model
R-Squared Test	***0.80***	***0.78***	***0.78***	***0.84***
Median Type	-	-	-	-
Median Width	0.41	0.38	0.29	-0.40
NEEnd	Yes	Yes	-	-
SWEnd	Yes	Yes	-	-
Length of Road	0.01	0.009	0.003	0.01
One-way	-5.9	-5.1	-7.2	-7.2
Midblock Ped X-ing	-	-	-	-2.0
Roadside	-	-	-	Yes
Width	-	-	-0.23	0.44
Number of Lanes	-	-	-	-
Parking	-	-	-	-
Walk	-	Yes	-	-
Total Blvd	-	-	0.25	0.13
Access Density	-	-0.04	-0.16	-0.03
Pole Density	-0.06	-	-0.11	0.15
Tree Density	-	-0.01	-0.02	0.008
Tree Maturity	-	-	-	-
Avg Offset	-	0.75	0.82	-0.29
Road Class	Yes	Yes	-	-
Posted Speed Limit	0.23	0.22	0.36	-0.18
Bus Stop	-	-	0.79	-1.03
Avg Veh Length	1.5	1.0	6.8	-0.7
Service Road	1.2	-	-	3.4
Bike Route	Yes	-	Yes	-

Table 12 Variables which influence speed variability

Variables*Z_p	All Model	A&C Model	Arterial Model	Collector Model
R-Squared Test	***0.80***	***0.78***	***0.78***	***0.84***
Median Type	-	-	-	-
Median Width	-	-	-	-
NEEnd	-	-	-	-
SWEnd	-	-	-	-
Length of Road	-	-	-	-
One-way	-	-	-	-2.5
Midblock Ped X-ing	-	-	-	-
Roadside	-	-	-	Yes
Width	-	-	-	-0.14
Number of Lanes	-	-	-	-
Parking	-	-	-	-
Walk	-	-	-	-
Total Blvd	-	-	-	-
Access Density	-	0.01	0.04	-
Pole Density	-	-	-	-
Tree Density	-.005	-	-	-
Tree Maturity	-	Yes	-	-
Avg Offset	-	-	-	-
Road Class	Yes	Yes	-	-
Posted Speed Limit	0.05	0.05	0.06	-
Bus Stop	-	-	-	-
Avg Veh Length	-	-	0.91	-
Service Road	-	-	-	-
Bike Route	-	-	-	-

4.1 Comparison of Models

The difference between the four models indicates that geometric features that affect operating speeds vary between road classifications. This is especially significant between the Collector and Arterial models, where some variables have opposite effects on operating speeds. Variables, such as median width, road width, object density, object offset, posted speed limit, the size of vehicle (percentage of trucks), and the presence of a bus stop, all have opposite effects on operating speeds between the A and C models (more discussion on each variable below). The variation of statistically significant variables between the two models means that creating a single unified urban operating speed model would need to take into account that the road class for every variable or Arterials and Collectors should be modeled separately.

The Arterial model was more consistent with findings on highway models than the Collector model. This is to be expected, since arterials are designed for higher speeds and volume of traffic when compared to collectors which are more for lower volume and local access. Also, the collector locations had more variation in facility types (geometric attributes) than arterial locations.

4.2 Medians

In the model, medians were broken into two variables: median width and median type. Between these two variables, only the median width was statistically significant. The median width estimates were 0.41, 0.38, 0.29, and -0.40 for All, A&C, A, and C models, respectively. Generally, these findings indicate that, for every meter in width of median, vehicle speeds increase by 0.3 to 0.4 km/h. However, in this study, this is not the case for the collector locations as the collector model had contrary findings to the other three.

The medians on the collector locations were found to lower driving speeds by 0.4 km/h. This may be explained by recognizing that the function of the medians on collectors may be significantly different than arterials. Six of the nine medians were lined with trees and planted areas. This may indicate that these median are used more for a community aesthetic rather than for strict engineering design. This results in collector medians having more of a traffic calming effect.

The models that include arterial locations have similar findings to Fitzpatrick et al.'s (2003) study. That study found that the most statistically significant feature was the width of the median area, including shared center turning lanes *(22)*.

In Tay and Churchill's (2007) study, which only examined the type of median, they focused primarily on the operating speeds of the adjacent lane. In future studies, separating traffic speeds by lanes may lead to a stronger correlation between median types and operating speeds *(24)*.

4.3 End Treatment (boundary conditions)

Previous studies only examined the impact of before and after curves on operating speeds. This study looked at four types of treatments on either end, intersection with right-of-way, curve, stop controlled intersection, and signalized intersection. In the larger data sets, A&C and All, the end treatments are statistically significant in reducing operating speeds. The impact of end treatments, when compared to an intersection where a vehicle has the right-of-way, signalized intersection had the greatest impact, followed by a stop controlled intersection and finally curves.

The A and C models did not indicate the end treatments as statistically significant. The impact of end treatments may be more apparent if they were studied in conjunction with the direction of the traffic flow, where there is an entering and exiting boundary condition.

Table 13 Summary of end treatment categorical variable

		Number of Locations per Classification per Model				Model Estimates	
	End Treatment (identifier in model)	All	A&C	A	C	**Speed** Portion for **All** Model	**Speed** Portion for **A&C** Model
NE End	Signalized Intersection (1)	79	78	66	12	-1.22	-1.49
	Stop controlled intersection (2)	16	10	2	8	-1.33	-4.94
	Curve (3)	20	17	7	10	-1.82	-1.20
	Intersection with right of way (4)	165	144	51	93	0.00	0.00
SW End	Signalized Intersection (1)	77	76	71	5	-4.65	-4.37
	Stop controlled intersection (2)	24	19	2	17	-2.58	-2.66
	Curve (3)	15	13	4	9	-1.97	-2.18
	Intersection with right of way (4)	164	141	49	92	0.00	0.00

4.4 Length of Road

All the models indicate that operating speeds increased with an increase in the length of road. The All, A&C, and C model show a 1 km/h increase for every 100 to 110 meters of addition tangent lengths. The A model shows a 1km/h for every additional 330 meters. This discrepancy between the Arterial model and other models could be largely due to the fact that arterials are significantly longer than other road classes. Arterials are, on average, twice the length of collectors. In other words, vehicles on collectors get much closer to their desired operating speed. Therefore, an increase of collector length has more impact on operating speeds than an increase in length of an arterial. This finding is substantiated by the distance most vehicles require to reach max speed.

Two studies can be used to roughly interpolate the distance to reach max speed on arterials and collectors. He et al. (2010) found that drivers on highways took, on average, 700 m to reach a max speed of 120 km/h in a 110 km/h posted speed zone *(21)*. Dinh and Kubota's (2013) found that drivers took, on average, 120 m to reach max speed where the posted speed was 30 km/h *(16)*. Assuming a linear relationship, the required distance to reach max speed for 50 and 60 km/h posted zones would be 260 m and 340 m, respectively. As most collectors are posted 50 km/h and arterials are 60 km/h, the average arterial length of 300 m is a lot closer to 340 m than the average collector length of 149 m is to 260 m.

Table 14 Summary of segment lengths by model

	All Model	A&C Model	A Model	C Model
Parameter Estimate	0.013	0.0089	0.0028	0.012
Average Length	216 m	226 m	300 m	149 m
Mean Length	173 m	180 m	232 m	119 m
Min Length	43 m	43 m	45 m	43 m
Max Length	1363 m	1363 m	1363 m	533 m

4.5 One-way

There were a total of seven one-way locations included in the study. They were split evenly between arterials and collectors, with four one-way arterial locations and three one-way collector locations. Depending on the model, one-ways reduced operating speeds between 5 km/h and 7 km/h. These findings are supported by Eluru et al.'s (2013) Montreal study, which also found that operating speeds were lower on one-ways *(19)*.

4.6 Midblock Pedestrian Crossings

There were a total of 14 midblock pedestrian crossings. They were divided evenly between arterial locations with five, and collector locations with six. If a pedestrian crossing is in use, it would force drivers to slow down and stop. As this study only examined free flow traffic, only how the presence of a pedestrian crossing (while not in use) impacts operating speeds was evaluated. It was established that pedestrian crossings statistically significantly impacted collector locations. Pedestrian crossings were found to reduce operating speeds by 2.0 km/h on collectors. No studies were found to compare these findings to. Originally, the type of pedestrian crossing was included as a categorical variable. However, there were not enough locations to make pedestrian crossings a viable categorical variable. To further study the impact of midblock crossings on operating speed, a before and after study could be conducted.

Table 15 Number of midblock pedestrian crossings per model

	All Model	A&C Model	A Model	C Model
Number of Midblock Ped x-ings	14	11	5	6

4.7 Roadside

Land use has been found to be statistically significant in operating speeds models for two lane rural highways. In an urban setting, land use is not as clear cut and there are more types of zoning. For instance, an arterial running through a residential land use area may be at one point flanked by detached residential homes while at another a single row of commercial businesses. Moreover, the land use does not differentiate between the intensity of use. For example, two streets, one with single detached family homes and the other with residential towers, would both be labeled residential. Most two lane models are for non-urban areas. In such areas, land use may act as a reasonable proxy for variables such as access density, parking condition, presence of sidewalks, etc. The models in this study use a roadside variable as a localized proxy for land use. The roadside variable better represents the density of buildings, offset of buildings, and pedestrian activity than zoning.

Roadside was only found to be statistically significant in one model, the C model. In the C model, the type of roadside was statistically significant for both operating speed and speed variability. Interestingly, mixed low density correlated to the highest speed but the lowest speed variability and mixed high to medium density had the lowest operating speeds but highest speed variability. Open urban was in the middle for both operating speed and speed variability. There were no collectors with downtown commercial type road sides.

Table 16 Summary of roadside categorical variable

	Number of Locations per Classification per Model				Model Estimates	
Roadside (identifier in model)	All	A&C	A	C	**Speed** Portion for **C** Model	**Speed Distribution** Portion for **C** Model
Downtown Commercial (1)	13	13	13	0	-	-
Mixed High to Medium Density (2)	19	18	15	3	-8.29	11.98
Mixed Low Density (3)	176	147	32	115	2.81	11.50
Open Urban (4)	72	71	66	5	0.00	11.82

4.8 Width and Number of Lanes

Road widths were found to be statistically significant in the A and C models, with opposite effects between the A and C models. In the C model, wider roads were correlated with higher speeds, where every additional meter of road width represented an increase of 0.4 km/h. This is consistent with findings on other studies.

The Arterial roads model had opposite findings. For every meter that roads were wider, operating speeds reduced by -0.23 km/h. This negative correlation may be more of a difference between an older and newer arterial design. Businesses typically abut older arterials and have one lane of off peak parking on either side. Arterials built since the 1970s have permanent parking bans on both sides and business parking is accommodated in parking lots. An example of this is location 283 and location 39. Location 39 near the downtown (109 Street north of 109 Avenue) is an undivided six lane road, where off-peak parking is allowed at certain locations along the corridor. This location has a total road width of 20 meters but only an average lane width of 3.3

meters. The V_{85} at this location on 109 Street is 66 km/h. Conversely, location 283 (23 Avenue west of Mill Woods Road) is further from the downtown and meets the new arterial design standard. It consists of divided four lanes where access is limited to the intersections and parking is banned on both sides at all times. The total road width is 17 meters or an average of 4.25 meters per lane. The V_{85} for this location is 71 km/h.

Several studies have considered lane width, carriageway (or road width), and number of lanes. The findings on lane widths were mixed, while carriageway and number of lanes were found to increase operating speed (see **2.2.4** and **2.2.14**). This study chose to look at carriageway widths and the number of lanes as they were strongly correlated. However, as number of lanes was not found to be statistically significant and road width had mixed findings, it is recommended in future studies of urban roads to explore lane widths or usable with of road during off-peak hours. Future studies that focus on individual lanes may also help determine the impact of lane widths.

4.9 Walk and Boulevard Area

Walks are statistically significant in the A&C model while boulevards are statistically significant in the A and C models. In the A&C model, boulevard walks on both sides were associated with the highest operating speeds, followed by any type of walk on one side, then boulevard walk on one side and monolithic walk on the other side, finally mono walk on both sides is correlated with the lowest speeds.

In both the A and C models, an increase in boulevard area correlates to higher operating speeds. In the Arterial model, a 1 m increase in boulevard area had a 0.25 km/h increase in operating speed. In the Collector model, a 1 m increase in boulevard had a 0.13 km/h increase in operating speeds.

Both the walk and boulevard variables indicate that, as walks are moved away from roads, operating speeds increase.

Table 17 Summary of walk categorical variable

	Number of Locations per Classification per Model				Model Estimates
Walk (identifier in model)	All	A&C	A	C	**Speed** Portion for **A&C** Model
Boulevard walk on both sides (1)	76	71	15	56	0.99
Boulevard walk on one side mono walk on other side (2)	49	40	24	16	-1.31
Mono walk on both sides (3)	84	69	23	46	-3.24
Walk on one side or no walk (4)	71	69	64	5	0.00

4.10 Access Density

The A&C, A, and C models all show a negative correlation between access density and operating speeds. Access density is measured by number of accesses per kilometer. For every access per kilometer, operating speeds drop by -0.04, -0.16, and -0.03 km/h for the A&C, A, and C models, respectively. These findings are similar to those in the literature.

The A&C and A models indicate a positive association between access density and speed percentiles.

4.11 Pole and Tree Density; Tree Maturity; and Average Offset

Both the A&C and A models show a reduction in operating speed as the number of objects and their nearness to the road increase. These models both indicate that, as tree density increases, operating speeds reduce. Likewise, they indicate that operating speeds reduce as the average offset of objects becomes closer to the road. Additionally, in the A model driving speeds reduce as pole densities increase.

Table 18 Collect pole and tree density example

Location ID	V_{85}	Pole Density Per Km	Tree Density Per Km	Average Object Offset (m)
237	66	21	167	2.6
323	69	24	183	1.7
504	50	8	33	3.1
539	55	23	23	3.2

In contrast, the C model found that operating speeds increased as object density and their proximity to the road increase. While this may seem counterintuitive, collectors vary from roads that have very similar properties to an arterial to those that are similar to residential roads. Below are snapshots of four collector locations from this study. The top two locations (237 and 323) have higher speeds, pole density, and tree density than the lower two locations (504 and 539). In the top two locations, objects are also closer to the road (see **Table 19**). These four examples are characteristics of collectors in this study. While the higher speed locations have, on average, more trees and objects that are closer to the road, this may be more related to the general design principals or when they were constructed.

Table 19 Comparison of collector locations

Location 323: 44 Avenue west of Jackson Road*(33)*

Location 237: 179 Avenue West of 92 Street*(34)*

Location 504: Delwood Road west of 67 Street*(35)*

Location 539: Leger Road west of Leger Way*(36)*

In the A&C model, speed distribution decreased with tree density.

Table 20 Summary of tree maturity categorical variable

	Number of Locations per Classification per Model				Model Estimates
Tree Maturity (identifier in model)	All	A&C	A	C	**Speed Distribution** Portion for **AC** Model
Mature trees on both sides (1)	150	133	65	68	6.86
Mixed age of trees on both sides or one side (2)	70	60	31	29	6.66
No trees or young trees on one side or both (3)	60	56	30	26	7.26

4.12 Road Class

As expected, arterial roads had higher operating speeds than collector roads. In the All model, a collector classification increased operating speeds by 7.3 km/h over local roads. An arterial classification increased operating speeds by 14.1 km/h over a local road classification or 6.8 km/h over a collector road. In the A&C model, arterial classification indicated a 5.1 km/h increase in operating speed over collector road.

Speed diversity also reduced as road classification moved from local to collector and, finally, arterial. This was evident in both the All and A&C models. The All model shows that local roads have the highest speed diversity, while the arterials have the lowest. The A&C model demonstrates that arterials speed diversity is lower compared to collectors.

Table 21 Summary of road class categorical variable

	Number of Locations per Classification per Model				Model Estimates			
Road Class (identifier in model)					**Speed** Portion for		**Speed Distribution** Portion for	
	All	A&C	A	C	**All** Mode	**A&C** Mode	**All** Model	**A&C** Model
Arterial (A)	126	126	126	0	14.07	5.05	6.43	-0.86
Collector (C)	123	123	0	123	7.32	0.00	7.54	0.00
Local (L)	31	0	0	0	0.00	-	8.82	-

4.13 Posted Speed Limit

The All, A&C and A Models were consistent with the literature indicating higher operating speeds in areas with higher posted speed limits. The C models indicated a negative correlation between posted speed and operating speed. The below table summarizes the average V_{85} for each posted speed zone along with the number of location by road class. From this table, it is clear that the majority of collector locations are posted at 50 km/h. Arterial locations, on the other hand, are split evenly between 50 km/h and 60 km/h zones.

The All, A&C, and A models had a positive association between posted speed limit and speed variability. This indicates that locations with higher posted speed limits had higher variability in operating speeds.

Table 22 Summary of posted speed limit zones by road class

Posted Speed Limit	Collector Locations		Arterial Locations	
	Number of Locations	Average V_{85} Speed for Posted Speed Limit (km/h)	Number of Locations	Average V_{85} Speed for Posted Speed Limit (km/h)
40	1	55.0	-	-
50	119	58.5	54	59.7
55	1	72.0	1	74.0
60	-	-	60	69.3
70	-	-	8	80.0
80	2	51.0	2	69.1
100	-	-	1	123.9

4.14 Bus Stop

Bus stops had opposite effects on arterials compared to collectors. On arterials, bus stops were correlated with locations with higher speeds. The presence of a bus stop on an arterial increased operating speeds by 0.79 km/h. The opposite was true for collectors, where the presence of a bus stop reduced operating speeds by 1.03 km/h. For both the arterial and collector models, approximately half the locations had bus stops. Of the 126 arterial locations, 78 had bus stops (62%) and, of the 123 collector locations, 63 had bus stops (49%).

The difference in the findings of the two models could be largely due to how busses operate on collector and arterial locations. Arterial locations tend to have two or more travel lanes on each side. When a bus stops at a bus stop, it often fully pulls out of the traffic flow. This is different from most collector locations, which only have a single travel lane in each direction. When a bus stops at a designated bus stop, it often reduces or obstructs the travel lane in that direction.

4.15 Average Vehicle Length

The average vehicle length acted as a proxy for percentage of trucks. All three models had a correlation between operating speed and average vehicle length. The All, A&C, and A model had operating speeds increase as the average vehicle length increased. Conversely, collector locations saw a drop in operating speeds as the average vehicle length increased. This indicates that if there is a causal relationship between larger vehicles and road classes, as opposed to simply correlation, then larger vehicles have opposite impacts on collectors as arterials. Again, assuming causation, larger vehicle push up the operating speeds on arterials whereas on collectors they reduced operating speeds. This makes sense when considering the use and size of these two types of facilitates. Arterials are larger and are typically used to move traffic through an area. Collectors, on the other hand, are often one lane and used for local access.

There was also a positive correlation between speed variability on arterials and larger vehicles.

4.16 Service Road

The All and C models showed a positive correlation between service roads and operating speeds. While there is a clear correlation with operating speeds on collectors with service roads increasing by 3.4 km/h, there were only three collector locations with service roads. It's likely that service roads increase operating speeds as they operate in two ways: they control access and they create a wider field of view. Arterials may not have demonstrated a correlation because a significant portion of arterials have similar attributes with wide boulevards/ building offsets and limited access.

4.17 Bike Route

Of the 280 locations, 13 had on road bike facilities. Bike facilities only considered marked bike lanes. This variable initially included a sharrows category. However, there was no difference between sharrows and no on road bike markings. Therefore, the two categories were combined. Of the 13 locations with marked bike lanes, 11 were on collectors and two were on arterials. Other than one arterial with a marked bike lane on one side, there was a strong correlation between bike lanes and operating speeds. This finding is consistent with the conclusions found in Eluru et al.'s (2013) study *(19)*. On average, within the All model bike lanes, operating speeds increased by 4.6 km/h.

Table 23 Summary of bike route categorical variable

	Number of Locations per Classification per Model				Model Estimates	
Bike Route (identifier in model)	All	A&C	A	C	**Speed** Portion for **All** Model	**Speed** Portion for **A** Model
Buffered bike lane on both sides (1)	2	2	0	2	8.20	-
Marked bike lane on one side and buffered bike lane on other side (2)	1	1	0	1	8.30	-
Marked bike lane on both sides of road (3)	9	9	1	8	5.06	11.63
Marked bike lane on one side of the road (4)	1	1	1	0	-5.00	-2.89
No bike markings or bike sharrows on either side of road (5)	267	236	124	112	0.00	0.00
Total number of locations with bike lanes	13	13	2	11		

5 Conclusion and Recommendations

5.1 Comparison of Findings to Similar Studies

This study built on the existing operating speed body of knowledge particularly in the urban environment. The majority of operating speed studies that have been completed using OLS estimation with a single operating speed (typically V_{85}). The majority of existing models focused on rural two lane highways. The fraction of studies that considered urban areas typically focused on one feature, including median treatments and 30 km/h residential roads, or attempted to model all geometric features. Of the latter category, there are currently only two models found in the literature: Wang et al.'s (2006) study and Eluru et al.'s (2013) study *(15, 19)*. This study was based on these two studies, as well as Median and Tarko's (2005) Highway model, which used panel data to research both operating speed and speed variability *(17)*. **Table 24** compares this study to Wang et al.'s (2006) and Eluru et al.'s (2013) findings.

Table 24 Comparison of urban operating speed studies

Study	Wang et al. (2006)	Eluru et al. (2013)	This Study
number of locations	200 vehicles with GPS on 35 locations	49 local, and 71 arterial (130 total)	31 Residential, 123 collector, and 126 arterial (280 total)
Model	Linear Mixed-effects model	Panel Mixed Order Probit Fractional Split model	Ordinary Least Squares Panel Data
Focus on tangents	Yes	Not explicitly controlled for	Yes
Number of models	V_{85} and V_{95} models	Local, arterial	All locations, arterial and collector, arterial only, and collector only
Response variable	85^{th} and 95^{th} percentile speed	Proportion of vehicles in speed categories from 20 km/h to 120 km/h in increments of 10 km/h	Panel of operating speeds corresponding to percentiles from the 5^{th} to 95^{th} in increments of five
Summary of Key Findings Affecting Operating Speed			

Table 24 Comparison of urban operating speed studies

Study	Wang et al. (2006)	Eluru et al. (2013)	This Study
Road width and number of lanes	The number of lanes had a positive correlation with operating speed	Increase in lanes correlated with an increase in operating speed	Road width was correlated with operating speed for collectors
One-ways	Not evaluated	Reduced operating speeds	Reduced operating speeds
Parking	Negative impact on operating speed	Negative impact on operating speed	Was not found to be statistically significant
Sidewalks	Presence of sidewalks correlated with lower speeds	More sidewalks correlate with higher speeds	Sidewalks further away from the road correlate with higher speeds. Mono walk on both sides was found to have the lowest operating speeds.
Bicycle Routes	Not evaluated	The presence of bicycle routes increases operating speeds	The presence of bicycle routes increase operating speeds
Segment Length	Not evaluated	Not evaluated (road segments between intersections less than 200m were dropped)	Higher operating speeds correlate with longer road segments
Percentage of Trucks	Not evaluated, GPS study was conducted with a selection of passenger vehicles	Not evaluated	On arterials correlated with higher operating speeds, on collectors correlated with lower operating speeds
Curb and Gutter	Positive correlation with operating speed	Not evaluated, although assumed that most if not all location had curb and gutter	Not evaluated, majority of locations had curb and gutter
Land Use	Slightly higher speeds in commercial areas	Not evaluated	Lower speeds on commercial roads as density increased
Access Density	Operating speeds decreased as driveway density increased	Not evaluated	Operating speeds decreased as accesses increased

Table 24 Comparison of urban operating speed studies

Study	Wang et al. (2006)	Eluru et al. (2013)	This Study
Intersections	T – intersections reduce operating speeds	Not evaluated	Signalized and stop control intersections reduce operating speeds
Posted Speed Limit	Posted speed limit was not included in the model. Want et al. argued that the posted speed limit was correlated to the geometric design	Higher operating speeds were correlated with higher speed limits	Higher operating speeds were correlated with higher speed limits
Roadside Object Density / Tree Density	Operating speed decreased as object density increased	Not evaluated	Operating speeds decreased as object density and/ or tree density increased on arterials
Midblock pedestrian crossing	Not evaluated	Not evaluated	Reduces operating speeds on collectors
Bus Stops	Not evaluated	Not evaluated	Bust stops were found to have opposite effects on arterials and collectors. On arterials bust stops were correlated with higher operating speeds while on collectors they were correlated with lower
Medians	Not evaluated	Not evaluated	A wider median on an arterial correlates to higher operating speeds
Summary of Key Findings Affecting Seed Variability			
Road Class	Not evaluated	Not evaluated	Speed variability was higher on collectors than arterials
One-Way	Not evaluated	Not evaluated	Collectors had lower speed variability on one-ways

Table 24 Comparison of urban operating speed studies

Study	Wang et al. (2006)	Eluru et al. (2013)	This Study
Roadside	Not evaluated	Not evaluated	The collector locations with the highest density also had the highest speed variability
Width	Not evaluated	Not evaluated	Wider collectors had lower speed variability
Access Density	Not evaluated	Not evaluated	The more access there are the higher the speed variability on arterials
Posted Speed Limit	Not evaluated	Not evaluated	The higher the posted speed limit the higher the speed variability on arterials
Percent Trucks	Not evaluated	Not evaluated	More trucks are correlated with higher speed variability on arterials

When comparing these three studies, where there was cross over, there was consistency between the models. In general, a wide road with less visual obstructions and access has higher operating speeds—this was obvious. What are less apparent are two findings that were supported by Eluru et al.'s (2013) research *(19)*. His study indicated that, first, one-ways have lower operating speeds and, second, that bike lanes encourage higher operating speeds.

While there were similarities, this study expanded the research further by using a much larger data set that included significantly more variables in the model. Finally, this study evaluated how each of the variables impacted speed variability.

5.2 Reducing Operating Speeds

Generally, there are several opportunities to reduce the operating speeds on a road section. With regards to the roadway, bringing traffic together by removing medians and narrowing travel lanes reduces operating speeds. For treatments along the side of the road, the more objects and access points there are, the slower the operating speed, including denser trees, poles, and access reduce operating speeds. Moving biking lanes off the road would also reduce operating speeds. The study found that locations with standard or buffered bike lanes had higher speeds. Finally, reducing the boulevard area and moving pedestrians closer to the road has an impact on reducing operating speeds.

There are two attributes that correlate with lower operating speeds but would be difficult to implement in existing urban area. These attributes include reducing the length of tangents by either increasing intersection density or adding curves, and introducing stop control at existing intersection with either a stop sign or signalized intersection. While these may not be practical for existing urban roads, they may be considered for the design of new arterial and collector roads.

There are also changes that could be implemented on a planning level. The road network could be changed to include more one-ways. Other than reducing operating speed, one-ways also increase through traffic volumes. The major down side to one-ways is the reduced local access. From a planning perspective, roads could be designed with smaller right of ways to encourage businesses to abut the roadway. This would allow for a smoother integration of some of the above design elements.

Posted speed limits have been shown to have a correlation with operating speeds. Reducing the speed limit would reduce operating speeds. However, if the issue with the given road sections is driver infractions, reducing the speed limit could arguably increase infractions while also reducing the overall operating speeds.

Based on the models, the above improvements generally work better on arterial or arterial-like roadways. Following is a discussion focused on collector locations.

5.2.1 Reducing Operating Speed on Collectors

Collectors can be broadly broken into major and minor collectors. The major collectors are typically the main artery into a community or through a community and are often designed to a standard that resembles an arterial design standard. Minor collectors are closer in design to residential roads with minimal road markings and direct residential access. As both major and minor collectors are in residential zones, they are almost exclusively both posted at 50 km/h. This leads to some attributes that are only found on major collectors associated with higher operating speeds. The two major attributes that are typically on major collectors (and not minor) include boulevard walks with tree lined streets with trees and streetlights in the boulevards, resulting in pole density, tree density, and smaller object offset being associated with higher operating speeds. That said, recommendations can be made based on this study to reduce operating speeds on collectors.

There are several elements of a collector roadway that can be altered to reduce operating speeds. The basic elements, such as road width and length, can be reduced. Adding resident and business access onto the collector also reduces operating speeds. Further, speed reduction can be attained by increasing the density and reducing the offset of buildings from the road. Where possible, collectors with service roads could be redesigned to eliminate the service road.

The use of medians on collectors is different than arterials. In this study, the majority of medians, on collectors, were tree lined with grass. This type of median, on collectors, seemingly had a calming effect on traffic and reduces driver speeds. Therefore, the presence of medians is neutral on collectors, given that the number of collector locations with medians was limited and the finding is contrary to the rest of the study. Median use on collectors, with respect to operating speed, can be summarized as follows: where medians are used as beatification, they will likely reduced operating speeds. On the other hand, if medians are added to reduce congestion, such as a two-way turning lane or to reduce access, they will likely increase operating speeds.

Bike lanes on collectors also have mixed conclusions. While it is clear that on higher speed locations like arterials, bike lanes are associated with higher operating speeds. The presence of bike lanes on more minor type collectors does not seem to have an impact. Therefore, removing bike lanes for major collectors may reduce operating speeds, while removing bike lanes from more minor collectors may not have an impact on operating speeds.

5.3 Speed Variability

When comparing collectors and arterials, arterials had less speed variability. However, this study found that speed variability on collectors is correlated with different attributes than arterials. On arterials, speed variability is correlated to the higher number of accesses, a higher speed limit, and higher number of trucks. This is different from collectors, where lower speed variability is correlated with one-ways, wider roads, and less dense areas. The wider roads on collectors is likely correlated with less speed variability as wider collectors function is closer to an arterial road which purpose is to move traffic rather than provide access which in turn reduces speed variability. It makes sense that speed variability reduces as roads move up the class scale from residential, which are designed for local access to highways, which have controlled access, and are built for conveyance.

5.4 Research Limitations and Future Recommendations

5.4.1 Research Limitations

This research has several limitations. First, the data set was very large and design guidelines/standard practices were not factored into the research. While factoring in design guidelines would be difficult as they have changed over the years, this would likely explain some of the conflicting findings between arterials and collectors. Section 4 Modelling Results and Discussion, explores some of the design guidelines or practices that may have led to conflicting results.

Second, this study considered whether parking was allowed but not its frequency or use. Considering the use or frequency would have required more detailed field observations of the parking at each location. This lack of data may be a cause for parking, which was significant in other studies, to not being statistically significant in this study. Due to the size of data set in this study there were significantly different parking situations where parking was allowed. For example, there were downtown/ main street type locations where on street parking use appeared to be frequent and well used. At the same time there were also residential collector locations which permitted on street parking but had very little use. Both these types of locations were indicated in the study as allowing parking.

Finally, this thesis, similar to other operating speed studies, only examined the statistical correlation between road attributes and operating speed. There is no discussion in this thesis of causation. Where correlated features such as wide lanes, and good sight lines fit within accepted design practices for high speed roadways, causation maybe reasonably straightforward. However, the link between correlation and causation is less clear for other statistically correlated features.

5.4.2 Future Recommendations

This thesis had the largest data set of locations to examine the impact of the urban environment on operating speeds. While this research had several findings, there are also areas that could use additional work:

- In future studies, road width should be measured differently between collectors and arterials. Arterials either have congested corridors with meters or other frequently used parking or parking is prohibited. Therefore, road width on arterials should be measured as usable road width. Most collectors allow parking which is often sparsely used. Thus, road width on collectors should be measured from the edge of road, as demonstrated in this study.
- Evaluate the impact of features by individual travel lane.
- To study causation, conduct longitudinal study of locations, where only a single variable is altered.
    - Conduct longitudinal study of locations using temporary measure, including a median barrier, reduced lane widths through line painting, the addition of bike lanes, reduced road width with barriers, tree planters on the road side, and so forth.
- To date, no studies have examined the impact of curb extensions (bulb-outs) at intersections on operating speeds. As this is a common feature of pedestrian oriented development and road dieting, its impact on traffic flow should be known.

- Evaluate two similar locations over time by using one as the control while, on the other, plant trees. Evaluate the impact of tree growth over time on operating speed.

5.4.3 Research Contributions

This thesis contributes to the operating speed modeling field by:

- modeling the largest urban data set (the data was arranged into four different models by road class);
- investigating arterial and collector locations separately (few previous studies have looked at arterials and collectors separately);
- using panel data (which increased the number of observations per location, allowed for more than one percentile to be considered, and allowed for the inclusion of speed variability);
- being the first urban road study to evaluate speed variability;
- being one of a limited number of studies to include class variables (this allows for a more detailed study of each variable);
- specifically studying variables which had conflicting findings (in the literature review, road attributes such as median treatment and road markings, sidewalks, land use, lane impacts, and the presence of truck traffic had conflicting findings);
- studying one-ways and bicycle routes (these had previously only been looked at in Eluru et al.'s (2013) study *(19)*);
- and by looking at several new variables which had not been previously studied (such as tree maturity and pedestrian).

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Appendix A – Model Results

All Model

The GLM Procedure

Class Level Information		
Class	**Levels**	**Values**
MedType	6	1 2 3 4 5 6
NEEnd	4	1 2 3 4
SWEnd	4	1 2 3 4
Roadside	4	1 2 3 4
Parking	3	1 2 3
Walk	4	1 2 3 4
RoadClass	3	A C L
BikeRoute	5	1 2 3 4 5
TreeMaturity	3	1 2 3

Number of Observations Read	5320
Number of Observations Used	5320

The GLM Procedure

Dependent Variable: PercValue

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	24	689845.4572	28743.5607	876.74	<.0001
Error	5295	173594.1247	32.7845		
Corrected Total	5319	863439.5819			

R-Square	Coeff Var	Root MSE	PercValue Mean
0.798950	11.06685	5.725778	51.73808

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Medianwidth	1	163318.7040	163318.7040	4981.58	<.0001
NEEnd	3	20988.4479	6996.1493	213.40	<.0001
SWEnd	3	6564.0358	2188.0119	66.74	<.0001
Lengthm	1	29752.2348	29752.2348	907.51	<.0001
oneway	1	2793.3963	2793.3963	85.20	<.0001
PoleDensityPerKm	1	1149.6293	1149.6293	35.07	<.0001
RoadClass	2	82143.3704	41071.6852	1252.78	<.0001
PSL	1	6454.4739	6454.4739	196.88	<.0001
AveVehLength	1	1317.8275	1317.8275	40.20	<.0001
ServiceRd	1	448.3629	448.3629	13.68	0.0002
BikeRoute	4	7662.5338	1915.6334	58.43	<.0001
TreeDenstiyPerKm*Zp	1	256882.5919	256882.5919	7835.48	<.0001
Zp*RoadClass	3	110009.6619	36669.8873	1118.51	<.0001
PSL*Zp	1	360.1868	360.1868	10.99	0.0009

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Medianwidth	1	24557.92732	24557.92732	749.07	<.0001
NEEnd	3	1885.80579	628.60193	19.17	<.0001
SWEnd	3	13350.14912	4450.04971	135.74	<.0001
Lengthm	1	15980.75084	15980.75084	487.45	<.0001
oneway	1	4161.89849	4161.89849	126.95	<.0001
PoleDensityPerKm	1	3626.82918	3626.82918	110.63	<.0001
RoadClass	2	59782.78200	29891.39100	911.75	<.0001
PSL	1	5458.42199	5458.42199	166.49	<.0001
AveVehLength	1	1674.77943	1674.77943	51.08	<.0001
ServiceRd	1	664.81017	664.81017	20.28	<.0001
BikeRoute	4	7662.53377	1915.63344	58.43	<.0001

The GLM Procedure

Dependent Variable: PercValue

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TreeDenstiyPerKm*Zp	1	241.71590	241.71590	7.37	0.0066
Zp*RoadClass	3	7029.40572	2343.13524	71.47	<.0001
PSL*Zp	1	360.18683	360.18683	10.99	0.0009

Parameter		Estimate		Standard Error	t Value	Pr > |t|
Intercept		21.28770838	B	1.45036965	14.68	<.0001
Medianwidth		0.40641975		0.01484956	27.37	<.0001
NEEnd	1	-1.21704399	B	0.22809041	-5.34	<.0001
NEEnd	2	-1.32523902	B	0.35360361	-3.75	0.0002
NEEnd	3	-1.81638019	B	0.33179978	-5.47	<.0001
NEEnd	4	0.00000000	B	.	.	.
SWEnd	1	-4.64910827	B	0.25020211	-18.58	<.0001
SWEnd	2	-2.58199202	B	0.29640992	-8.71	<.0001
SWEnd	3	-1.97133892	B	0.35922513	-5.49	<.0001
SWEnd	4	0.00000000	B	.	.	.
Lengthm		0.01313646		0.00059500	22.08	<.0001
oneway		-5.86044609		0.52013905	-11.27	<.0001
PoleDensityPerKm		-0.06020415		0.00572397	-10.52	<.0001
RoadClass	A	14.07151345	B	0.33050606	42.58	<.0001
RoadClass	C	7.31990849	B	0.28445846	25.73	<.0001
RoadClass	L	0.00000000	B	.	.	.
PSL		0.23574707		0.01827037	12.90	<.0001
AveVehLength		1.54778169		0.21655361	7.15	<.0001
ServiceRd		1.18774595		0.26376020	4.50	<.0001
BikeRoute	1	8.19579803	B	0.96706800	8.47	<.0001
BikeRoute	2	8.29737900	B	1.33910393	6.20	<.0001
BikeRoute	3	5.05679247	B	0.46016904	10.99	<.0001
BikeRoute	4	-5.00048294	B	1.34270730	-3.72	0.0002
BikeRoute	5	0.00000000	B	.	.	.
TreeDenstiyPerKm*Zp		-0.00501010		0.00184514	-2.72	0.0066
Zp*RoadClass	A	6.42888241		0.93647960	6.86	<.0001
Zp*RoadClass	C	7.54195355		0.84736204	8.90	<.0001
Zp*RoadClass	L	8.82234949		0.86596521	10.19	<.0001
PSL*Zp		0.05286392		0.01594887	3.31	0.0009

Arterial and Collector Model

The GLM Procedure

Class Level Information		
Class	**Levels**	**Values**
MedType	6	1 2 3 4 5 6
NEEnd	4	1 2 3 4
SWEnd	4	1 2 3 4
Roadside	4	1 2 3 4
Parking	3	1 2 3
Walk	4	1 2 3 4
RoadClass	2	A C
BikeRoute	5	1 2 3 4 5
TreeMaturity	3	1 2 3

Number of Observations Read	4731
Number of Observations Used	4731

The SAS System

The GLM Procedure

Dependent Variable: PercValue

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	24	548286.9086	22845.2879	704.00	<.0001
Error	4706	152712.7060	32.4506		
Corrected Total	4730	700999.6146			

R-Square	Coeff Var	Root MSE	PercValue Mean
0.782150	10.70739	5.696546	53.20201

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Medianwidth	1	136622.1454	136622.1454	4210.15	<.0001
NEEnd	3	11364.1873	3788.0624	116.73	<.0001
SWEnd	3	4973.4328	1657.8109	51.09	<.0001
Lengthm	1	26801.8835	26801.8835	825.93	<.0001
oneway	1	4079.6908	4079.6908	125.72	<.0001
Walk	3	16479.7047	5493.2349	169.28	<.0001
AccessesDensityPerkm	1	3447.3583	3447.3583	106.23	<.0001
TreeDenstiyPerKm	1	1619.5627	1619.5627	49.91	<.0001
AvgOffset	1	6093.5196	6093.5196	187.78	<.0001
RoadClass	1	18126.7128	18126.7128	558.59	<.0001
PSL	1	4477.7141	4477.7141	137.99	<.0001
AveVehLength	1	642.2469	642.2469	19.79	<.0001
AccessesDensityPe*Zp	1	145154.7831	145154.7831	4473.09	<.0001
Zp*TreeMaturity	3	167845.8994	55948.6331	1724.12	<.0001
Zp*RoadClass	1	246.7263	246.7263	7.60	0.0058
PSL*Zp	1	311.3409	311.3409	9.59	0.0020

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Medianwidth	1	22022.22627	22022.22627	678.64	<.0001
NEEnd	3	5256.32919	1752.10973	53.99	<.0001
SWEnd	3	11783.52123	3927.84041	121.04	<.0001
Lengthm	1	5878.55046	5878.55046	181.15	<.0001
oneway	1	3008.31319	3008.31319	92.70	<.0001
Walk	3	9521.72014	3173.90671	97.81	<.0001
AccessesDensityPerkm	1	1972.43671	1972.43671	60.78	<.0001
TreeDenstiyPerKm	1	1482.34996	1482.34996	45.68	<.0001
AvgOffset	1	5084.54336	5084.54336	156.69	<.0001

The GLM Procedure

Dependent Variable: PercValue

Source	DF	Type III SS	Mean Square	F Value	Pr > F
RoadClass	1	13085.34553	13085.34553	403.24	<.0001
PSL	1	4480.16756	4480.16756	138.06	<.0001
AveVehLength	1	642.24687	642.24687	19.79	<.0001
AccessesDensityPe*Zp	1	256.50362	256.50362	7.90	0.0050
Zp*TreeMaturity	2	147.90235	73.95117	2.28	0.1025
Zp*RoadClass	1	485.76851	485.76851	14.97	0.0001
PSL*Zp	1	311.34093	311.34093	9.59	0.0020

Parameter		Estimate		Standard Error	t Value	Pr > |t|
Intercept		33.09269674	B	1.62581063	20.35	<.0001
Medianwidth		0.38485611		0.01477336	26.05	<.0001
NEEnd	1	-1.48996105	B	0.22150758	-6.73	<.0001
NEEnd	2	-4.93957470	B	0.43938174	-11.24	<.0001
NEEnd	3	-1.20198631	B	0.35903185	-3.35	0.0008
NEEnd	4	0.00000000	B	.	.	.
SWEnd	1	-4.37344637	B	0.24862428	-17.59	<.0001
SWEnd	2	-2.66083135	B	0.32953133	-8.07	<.0001
SWEnd	3	-2.18283574	B	0.38951827	-5.60	<.0001
SWEnd	4	0.00000000	B	.	.	.
Lengthm		0.00887046		0.00065906	13.46	<.0001
oneway		-5.06029994		0.52556491	-9.63	<.0001
Walk	1	0.99605872	B	0.32405613	3.07	0.0021
Walk	2	-1.30735367	B	0.31118145	-4.20	<.0001
Walk	3	-3.23674948	B	0.29982616	-10.80	<.0001
Walk	4	0.00000000	B	.	.	.
AccessesDensityPerkm		-0.03758963		0.00482146	-7.80	<.0001
TreeDenstiyPerKm		-0.01259975		0.00186422	-6.76	<.0001
AvgOffset		0.74675939		0.05965768	12.52	<.0001
RoadClass	A	5.05144741	B	0.25155611	20.08	<.0001
RoadClass	C	0.00000000	B	.	.	.
PSL		0.21719281		0.01848460	11.75	<.0001
AveVehLength		1.01717022		0.22864108	4.45	<.0001
AccessesDensityPe*Zp		0.01483192		0.00527548	2.81	0.0050
Zp*TreeMaturity	1	6.85794314	B	0.83659614	8.20	<.0001
Zp*TreeMaturity	2	6.66538005	B	0.84110814	7.92	<.0001

The GLM Procedure

Dependent Variable: PercValue

Parameter		Estimate		Standard Error	t Value	Pr > |t|
Zp*TreeMaturity	3	7.26356189	B	0.89812973	8.09	<.0001
Zp*RoadClass	A	-0.85898632	B	0.22201545	-3.87	0.0001
Zp*RoadClass	C	0.00000000	B	.	.	.
PSL*Zp		0.05023492		0.01621807	3.10	0.0020

Note: The X'X matrix has been found to be singular, and a generalized inverse was used to solve the normal equations. Terms whose estimates are followed by the letter 'B' are not uniquely estimable.

Arterial Model

The GLM Procedure

Class Level Information		
Class	**Levels**	**Values**
MedType	6	1 2 3 4 5 6
NEEnd	4	1 2 3 4
SWEnd	4	1 2 3 4
Roadside	4	1 2 3 4
Parking	3	1 2 3
Walk	4	1 2 3 4
RoadClass	1	A
BikeRoute	3	3 4 5
TreeMaturity	3	1 2 3

Number of Observations Read	2394
Number of Observations Used	2394

The GLM Procedure

Dependent Variable: PercValue

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	17	315551.6218	18561.8601	736.52	<.0001
Error	2376	59880.5225	25.2022		
Corrected Total	2393	375432.1443			

R-Square	Coeff Var	Root MSE	PercValue Mean
0.840502	8.756114	5.020183	57.33346

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Medianwidth	1	85853.81839	85853.81839	3406.59	<.0001
Lengthm	1	15000.00179	15000.00179	595.19	<.0001
oneway	1	3392.20677	3392.20677	134.60	<.0001
Width	1	2835.44017	2835.44017	112.51	<.0001
TotalBlvd	1	1294.38551	1294.38551	51.36	<.0001
AccessesDensityPerkm	1	9919.77043	9919.77043	393.61	<.0001
PoleDensityPerKm	1	17283.46463	17283.46463	685.79	<.0001
TreeDenstiyPerKm	1	2065.85929	2065.85929	81.97	<.0001
AvgOffset	1	8447.92040	8447.92040	335.21	<.0001
PSL	1	12672.69743	12672.69743	502.84	<.0001
BusStop	1	99.08525	99.08525	3.93	0.0475
AveVehLength	1	6187.99721	6187.99721	245.53	<.0001
BikeRoute	2	2098.41092	1049.20546	41.63	<.0001
AccessesDensityPe*Zp	1	83539.65132	83539.65132	3314.77	<.0001
PSL*Zp	1	64255.57596	64255.57596	2549.60	<.0001
AveVehLength*Zp	1	605.33631	605.33631	24.02	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Medianwidth	1	9489.528796	9489.528796	376.54	<.0001
Lengthm	1	548.312667	548.312667	21.76	<.0001
oneway	1	3253.891978	3253.891978	129.11	<.0001
Width	1	1854.612087	1854.612087	73.59	<.0001
TotalBlvd	1	1548.005153	1548.005153	61.42	<.0001
AccessesDensityPerkm	1	5428.296609	5428.296609	215.39	<.0001
PoleDensityPerKm	1	6786.726399	6786.726399	269.29	<.0001
TreeDenstiyPerKm	1	1587.507178	1587.507178	62.99	<.0001
AvgOffset	1	2973.335086	2973.335086	117.98	<.0001

The GLM Procedure

Dependent Variable: PercValue

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PSL	1	5483.142602	5483.142602	217.57	<.0001
BusStop	1	267.376318	267.376318	10.61	0.0011
AveVehLength	1	5803.487150	5803.487150	230.28	<.0001
BikeRoute	2	2098.410917	1049.205458	41.63	<.0001
AccessesDensityPe*Zp	1	464.938607	464.938607	18.45	<.0001
PSL*Zp	1	357.908302	357.908302	14.20	0.0002
AveVehLength*Zp	1	605.336311	605.336311	24.02	<.0001

Parameter	Estimate		Standard Error	t Value	Pr > |t|
Intercept	6.76696372	B	2.61302229	2.59	0.0097
Medianwidth	0.29403940		0.01515314	19.40	<.0001
Lengthm	0.00279778		0.00059982	4.66	<.0001
oneway	-7.21795978		0.63523214	-11.36	<.0001
Width	-0.23542793		0.02744423	-8.58	<.0001
TotalBlvd	0.25432533		0.03245062	7.84	<.0001
AccessesDensityPerkm	-0.15529274		0.01058130	-14.68	<.0001
PoleDensityPerKm	-0.11549656		0.00703815	-16.41	<.0001
TreeDenstiyPerKm	-0.01776252		0.00223803	-7.94	<.0001
AvgOffset	0.81634308		0.07515716	10.86	<.0001
PSL	0.35539643		0.02409450	14.75	<.0001
BusStop	0.78934256		0.24233918	3.26	0.0011
AveVehLength	6.76244240		0.44563433	15.17	<.0001
BikeRoute 3	11.62929726	B	1.34569534	8.64	<.0001
BikeRoute 4	-2.89393866	B	1.18486903	-2.44	0.0147
BikeRoute 5	0.00000000	B	.	.	.
AccessesDensityPe*Zp	0.04479193		0.01042849	4.30	<.0001
PSL*Zp	0.06422420		0.01704246	3.77	0.0002
AveVehLength*Zp	0.91467430		0.18663268	4.90	<.0001

Note: The X'X matrix has been found to be singular, and a generalized inverse was used to solve the normal equations. Terms whose estimates are followed by the letter 'B' are not uniquely estimable.

Collector Model

The GLM Procedure

Class Level Information		
Class	**Levels**	**Values**
MedType	5	1 3 4 5 6
NEEnd	4	1 2 3 4
SWEnd	4	1 2 3 4
Roadside	3	2 3 4
Parking	2	1 3
Walk	4	1 2 3 4
RoadClass	1	C
BikeRoute	4	1 2 3 5
TreeMaturity	3	1 2 3

Number of Observations Read	2337
Number of Observations Used	2337

The GLM Procedure

Dependent Variable: PercValue

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	21	187145.5326	8911.6920	370.39	<.0001
Error	2315	55699.3519	24.0602		
Corrected Total	2336	242844.8844			

R-Square	Coeff Var	Root MSE	PercValue Mean
0.770638	10.01662	4.905119	48.96979

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Medianwidth	1	1119.4969	1119.4969	46.53	<.0001
Lengthm	1	219.7945	219.7945	9.14	0.0025
oneway	1	2446.7393	2446.7393	101.69	<.0001
Midblockpedxing	1	138.6533	138.6533	5.76	0.0164
Roadside	2	2742.0653	1371.0327	56.98	<.0001
Width	1	3806.9668	3806.9668	158.23	<.0001
TotalBlvd	1	776.2408	776.2408	32.26	<.0001
AccessesDensityPerkm	1	319.2270	319.2270	13.27	0.0003
PoleDensityPerKm	1	7009.7056	7009.7056	291.34	<.0001
TreeDenstiyPerKm	1	339.3228	339.3228	14.10	0.0002
AvgOffset	1	472.7259	472.7259	19.65	<.0001
PSL	1	765.3781	765.3781	31.81	<.0001
BusStop	1	477.1676	477.1676	19.83	<.0001
AveVehLength	1	264.7940	264.7940	11.01	0.0009
ServiceRd	1	508.7265	508.7265	21.14	<.0001
oneway*Zp	1	2682.7871	2682.7871	111.50	<.0001
Zp*Roadside	3	162877.1063	54292.3688	2256.52	<.0001
Width*Zp	1	178.6348	178.6348	7.42	0.0065

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Medianwidth	1	502.859778	502.859778	20.90	<.0001
Lengthm	1	1300.075508	1300.075508	54.03	<.0001
oneway	1	2111.473883	2111.473883	87.76	<.0001
Midblockpedxing	1	400.826755	400.826755	16.66	<.0001
Roadside	2	5839.096370	2919.548185	121.34	<.0001
Width	1	1273.950116	1273.950116	52.95	<.0001
TotalBlvd	1	162.271780	162.271780	6.74	0.0095

The GLM Procedure

Dependent Variable: PercValue

Source	DF	Type III SS	Mean Square	F Value	Pr > F
AccessesDensityPerkm	1	965.420384	965.420384	40.13	<.0001
PoleDensityPerKm	1	5798.491790	5798.491790	241.00	<.0001
TreeDenstiyPerKm	1	194.094427	194.094427	8.07	0.0045
AvgOffset	1	273.878856	273.878856	11.38	0.0008
PSL	1	1048.146769	1048.146769	43.56	<.0001
BusStop	1	513.409313	513.409313	21.34	<.0001
AveVehLength	1	242.100071	242.100071	10.06	0.0015
ServiceRd	1	508.726503	508.726503	21.14	<.0001
oneway*Zp	1	241.082754	241.082754	10.02	0.0016
Zp*Roadside	3	9176.789418	3058.929806	127.14	<.0001
Width*Zp	1	178.634823	178.634823	7.42	0.0065

Parameter		Estimate		Standard Error	t Value	Pr > |t|
Intercept		49.79017925	B	2.47733872	20.10	<.0001
Medianwidth		-0.39509098		0.08642179	-4.57	<.0001
Lengthm		0.01241775		0.00168931	7.35	<.0001
oneway		-7.20313547		0.76891494	-9.37	<.0001
Midblockpedxing		-1.99458380		0.48867881	-4.08	<.0001
Roadside	2	-8.28646727	B	1.01147435	-8.19	<.0001
Roadside	3	2.80671208	B	0.69037994	4.07	<.0001
Roadside	4	0.00000000	B	.	.	.
Width		0.43741945		0.06011342	7.28	<.0001
TotalBlvd		0.13066270		0.05031294	2.60	0.0095
AccessesDensityPerkm		-0.03005686		0.00474499	-6.33	<.0001
PoleDensityPerKm		0.14976359		0.00964713	15.52	<.0001
TreeDenstiyPerKm		0.00755591		0.00266030	2.84	0.0045
AvgOffset		-0.28551676		0.08462563	-3.37	0.0008
PSL		-0.18063016		0.02736710	-6.60	<.0001
BusStop		-1.02935401		0.22283452	-4.62	<.0001
AveVehLength		-0.71633661		0.22582357	-3.17	0.0015
ServiceRd		3.39989458		0.73938876	4.60	<.0001
oneway*Zp		-2.54145259		0.80287607	-3.17	0.0016
Zp*Roadside	2	11.98378165		1.01039032	11.86	<.0001
Zp*Roadside	3	11.49597711		0.63614945	18.07	<.0001

The GLM Procedure

Dependent Variable: PercValue

Parameter		Estimate		Standard Error	t Value	Pr > |t|
Zp*Roadside	4	11.81673873		1.08944778	10.85	<.0001
Width*Zp		-0.13997863		0.05137221	-2.72	0.0065

Note: The X'X matrix has been found to be singular, and a generalized inverse was used to solve the normal equations. Terms whose estimates are followed by the letter 'B' are not uniquely estimable.

Appendix B – Federal Highway Administration Roadside Hazard Rating (RHR)

Appendix D - Prediction of the Expected Safety Performance of Rural Two-Lane Highways, month 2010

This report is an archived publication and may contain dated technical, contact, and link information

Publication Number: FHWA-RD-99-207 Prediction of the Expected Safety Performance of Rural Two-Lane Highways

APPENDIX D

DEFINITIONS OF ROADSIDE HAZARD RATINGS USED WITH THE ACCIDENT PREDICTION ALGORITHM

The accident prediction algorithm uses a roadside hazard rating system developed by Zegeer, et al. to characterize the accident potential for roadside designs found on two-lane highways.[6] Roadside hazard is ranked on a seven-point categorical scale from 1 (best) to 7 (worst). The seven categories of roadside hazard rating are defined as follows:

Rating = 1

- Wide clear zones greater than or equal to 9 m (30 ft) from the pavement edgeline.
- Sideslope flatter than 1:4.
- Recoverable.

Rating = 2

- Clear zone between 6 and 7.5 m (20 and 25 ft) from pavement edgeline.
- Sideslope about 1:4.
- Recoverable.

Rating = 3

- Clear zone about 3 m (10 ft) from pavement edgeline.

- Sideslope about 1:3 or 1:4.
- Rough roadside surface.
- Marginally recoverable.

Rating = 4

- Clear zone between 1.5 and 3 m (5 to 10 ft) from pavement edgeline.
- Sideslope about 1:3 or 1:4.
- May have guardrail (1.5 to 2 m [5 to 6.5 ft] from pavement edgeline).
- May have exposed trees, poles, or other objects (about 3 m or 10 ft from pavement edgeline).
- Marginally forgiving, but increased chance of a reportable roadside collision.

Rating = 5

- Clear zone between 1.5 and 3 m (5 to 10 ft) from pavement edgeline.
- Sideslope about 1:3.
- May have guardrail (0 to 1.5 m [0 to 5 ft] from pavement edgeline).
- May have rigid obstacles or embankment within 2 to 3 m (6.5 to 10 ft) of pavement edgeline.
- Virtually non-recoverable.

Rating = 6

- Clear zone less than or equal to 1.5 m (5 ft).
- Sideslope about 1:2.
- No guardrail.
- Exposed rigid obstacles within 0 to 2 m (0 to 6.5 ft) of the pavement edgeline.
- Non-recoverable.

Rating = 7

- Clear zone less than or equal to 1.5 m (5 ft).
- Sideslope 1:2 or steeper.
- Cliff or vertical rock cut.
- No guardrail.
- Non-recoverable with high likelihood of severe injuries from roadside collision.

Figures 8 through 14 present photographs illustrating the seven roadside hazard rating categories.

Figure 8. Typical Roadway with Roadside Hazard Rating Equal to 1.

Figure 9. Typical Roadway with Roadside Hazard Rating Equal to 2.

Figure 10. Typical Roadway with Roadside Hazard Rating Equal to 3.

Figure 11. Typical Roadway with Roadside Hazard Rating Equal to 4.

Figure 12. Typical Roadway with Roadside Hazard Rating Equal to 5.

Figure 13. Typical Roadway with Roadside Hazard Rating Equal to 6.

Figure 14. Typical Roadway with Roadside Hazard Rating Equal to 7.

Appendix C – Vaisala Nu-Metrics Portable Traffic Analyzer

Vaisala Nu-Metrics Portable Traffic Analyzer NC200

The Vaisala Nu-Metrics Portable Traffic Analyzer NC200 is designed to provide accurate count, speed, and classification data. The sensor is placed directly in the traffic lane to measure data, and can be installed and removed quickly and easily. The NC-100 model provides count only, while the NC-200 model provides count, speed and classification of vehicles.

The traffic analyzer combines accuracy and portability, monitoring traffic flow conditions right where you need them. Whether you are surveying traffic on a local roadway, bridge, parking garage, construction area, or in and out of local points of interest, the sensor provide key data necessary for effective traffic analysis.

The sensor utilizes Vehicle Magnetic Imaging (VMI) technology to detect vehicle count, speed and classification. The data is easily exported to Highway Data Management (HDM) software, where it can be presented in the form of reports, charts and graphs.

Benefits

- Portable sensor detects vehicle count, speed and classification
- Can be installed and removed in minutes
- Less noticeable to traffic, which results in more accurate information

Applications

- Traffic studies
- Parking lots, garages, and shopping centers
- Temporary studies for roadway planning
- Construction zones
- Airports, stadiums, and casinos
- Military bases and border crossings
- Parks or recreational areas
- Police departments (for speed studies)
- Stop signs, traffic lights, or posted speeds

Features

- Accurately measures vehicle count, speed, and classification
- Categorizes traffic into bins or by individual vehicle
- 15 speed bins and 13 length classification bins (configurable)
- Durable extruded aluminum housing
- Long life, rechargeable, Lithium-ion battery
- Connects to any computer for easy data retrieval
- Easy to use software for viewing data
- Software allows you to change your parameters after the study

Technical data

General

Housing Material	Extruded/anodized aluminum
Ultimate Bearing Strength	88,000 psi (607 Mpa)
Dimensions	181 x 118 x 12.7 millimeters (7.125 x 4.625 x 0.5 inches)
Weight	0.59 kg (1.3 lbs)
Operating Temperature	-20 C to +60 C (-4 F to +140 F)
Sensor	GMR magnetic chip for Vehicle Magnetic Imaging
Memory	Micro Serial Flash: 3MB
Battery/Power	Lithium-ion rechargeable (up to 21 days before recharge)
Computed Values	Imperial or Metric
Capacity	Up to 300,000 vehicles or 21 days per study, whichever occurs first
Length Classification* (% of Volume)	13 bins (user selectable length range)
Speed Classification* (% of Volume)	15 bins (user selectable speed range)
Vehicle Detection	Detects vehicles between 13 & 193 kph (8 to 120 mph)

CE COMPLIANCE
- EN-55022:1998 Emissions
- EN-55024:1998 Immunity
- EN-60950:2002 Low Voltage

*NC200 feature/specification only

Performance

Battery/Power	Lithium I_{on} Rechargeable 3.0 - 4.20 VDC, 3000 mAH at 23 C Nominal voltage 3.70 VDC (Up to 21 days before recharge) Automatic overcharge protection Field replaceable by customer
Accuracy length classification	+/- 4 ft, 90 % of the time
Accuracy speed classification	+/- 4 mph, 90 % of the time
Accuracy vehicle count determination	+/- 1%; 95 % of the time
Vehicle Detection	vehicles between 13 & 193 kph (8 to 120 mph)

For more information, visit www.vaisala.com or contact us at sales@vaisala.com

CE