Operating Speed Models for Tangent Segments on Urban Roads

Avi Thiessen, M.Sc.
Department of Civil and Environmental Engineering
University of Alberta, Edmonton, AB, Canada
+1-780-246-7376
Email: avi.thiessen@gmail.com

Karim El-Basyouny, Ph.D., P.Eng.
Department of Civil and Environmental Engineering
University of Alberta, Edmonton, AB, Canada
+1-780-492-9564
Email: basyouny@ualberta.ca

Suliman Gargoum, M.Sc.*
Department of Civil and Environmental Engineering
University of Alberta, Edmonton, AB, Canada
+1-780-200-0161
Email: gargoum@ualberta.ca

* Corresponding Author

Submitted for presentation at the 96th Annual Meeting of Transportation Research Board and publication in *Transportation Research Record: Journal of the Transportation Research Board*

TRB 96th Annual Meeting, Washington, D.C.
January 9-12, 2017

Word count: 6736 words + 4(4 Tables)*250 = 7500 equivalent words

ABSTRACT

Information about operating speeds is essential to design better roads, model traffic emissions, ensure design consistency while maintaining efficient and safe operations on our roads. Therefore, understanding how different factors affect operating speeds and developing operating speed prediction models is a critical research issue. Many studies have developed such models on rural roads and highways, but only a few studies have considered developing such models on urban roads, and fewer yet on tangential segments. Therefore, this paper attempts to address the abovementioned limitations by developing operating speed models using data from 249 tangential road segments in the City of Edmonton, Canada. The paper develops a Generalized Linear Model using panel data with the primary aim of exploring the relationships between operating speeds on urban roads and features of the road environment. In order to study the impact of road elements on different road types, three models were created: one including arterial and collector locations combined and two other models for arterial and collector roads separately. The results revealed that roads with sidewalks that were farther away from the road and with low object density and/or tree density were all associated with higher operating speeds. Locations with monolithic walk on both sides of the road had the lower operating speeds. Furthermore, operating speeds decreased as access increased while longer road had higher operating speeds. One major takeaway was that the elements differed between road classes. The two variables, which stood out in that respect, were medians and bus stops.

Keywords: Operating Speed; Speed Variability; Urban Roads; Panel Data; Generalized Linear Model

1. INTRODUCTION

The majority of geometric design guidelines in North America recommend using an minimum design speeds when designing new roads. Although designers are encouraged to adopt a higher standard to increase the factor of safety wherever possible, this is not always the case (*1*), the design speed is often either arbitrarily chosen or selected based on the geometric attributes of vertical and horizontal curves. In case of tangent or straight sections using such values can often result in the segments being over designed. Unfortunately, this design approach results in dichotomy between successive roadway elements leading to a non-uniform driving performance, reduces driver comfort and a potential increase in crash rates(*2*).

Watson Jr, Al-Kaisy and Anderson (*3)* found that the frequency of crashes rises with an increase in difference between free-flow speeds and design speed or posted speed limit. Therefore, it is necessary that roads are designed to closely match operating speeds expected on a certain roadway. Since operating speed prediction models use factors of the road environment in their prediction, such models would also help designers set speeds which are more consistent with the road environment. Hence, increasing the credibility of speed limits and yielding higher compliance rates (*4*).

To date most operating speed models have focused on two-lane rural highways and specifically road curves. The literature has shown that operating speeds on curves are closely linked to the radius of the curve or variations thereof. To the best of the authors' knowledge, only a few studies have examined tangents (*2; 5; 6*) and even fewer have focused on tangents in urban areas (*5; 6*). One reason why researchers have been reluctant to analyze operating speeds on such roads is because driver speed behavior is considered to be more complex on such segments. Unlike curved segments, where the curve's radius and degree of curvature have a huge influence on a drivers speed choice, there are a variety of factors that could affect a driver's choice of speed on tangent segments (*7*). There is also a lack of studies which analyze speed variability on road segments along with modelling operating speed. As a result, the TRB Synthesis Report recommends that future models be able to "distinguish mean speed factors from speed dispersion factors" (*8*).

In terms of the methodology, most operating speed models were developed using Ordinary Least Squares (OLS). For instance, in the 2011 TRC Synthesis Report on Operating Speed, over 90% of the studies used OLS (*8*). Despite its simplicity, 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.

Consequently, the aim of this paper is twofold (i) understand how features of the road environment and design elements affect operating speeds in an urban setting and (ii) develop parsimonious operating speed prediction models on urban tangential roads (i.e. non-curved segments). The paper contributes to the existing body of research on operating speed by analyzing data on urban roads rather than rural roads, analyzing data on tangential segments rather than curves, and analyzing speed variability on road segments in addition to operating speeds.

2. LITERATURE REVIEW

Polus, Fitzpatrick and Fambro (*2)* were the earliest to develop operating speed models for tangent segments on rural highways. The primary predictor of speeds was the properties of the horizontal curves at either end of the segment. The model was derived using ordinary least-squares (OLS) regression and the 85th percentile speed data was used as the response variable. The paper developed four models two of which had acceptable prediction power (R^2>0.5).

In one of the few studies that analyzed operating speeds on urban roads, Ali, Flannery and Venigalla (*9)* developed an OLS model using speed data from urban streets in Virginia, US. The authors found Posted Speed Limit (PSL), median width, and segment lengths to be the main factors affecting operating speed.

Fitzpatrick et al. (*5)* examined suburban arterials in six cities across Texas. The study developed regression models for both horizontal curves and tangent sections. For tangent sections, they found lane widths and PSL to be the only two statistically significant factors affecting operating speeds.

In 2005, Fitzpatrick et al. (*10)* specifically examined operating speeds on tangents. The study found that longer distance between features, large shoulder, wider road, and a wider median were associated with higher speeds. Other features were associated with lower speeds, including shorter signal density, absence of centerline, on street parking, and no median. The PSL was the only variable were associated with higher or lower operating speed.

Wang et al. (*11)* created continuous operating speed profiles to quantify the impact of geometric features on the profile in a low speed urban setting. The data was collected using GPS devices. A Linear Mixed-Effect Model was developed to account for the correlation between speed profiles of individual vehicles and drivers between different locations. The study found that variables with statistically significant effects on operating speeds 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. Based on their research, the authors concluded that drivers and vehicle are responsible for 35% of the unexplained variance.

The Design Consistency Model (DCM), a speed prediction model released by the FHWA as part of the Interactive Highway Safety Design Model (IHSDM) program (*8*), uses the radius of curves, the PSL and the Roadside Hazard Rating (RHR) of the road segment when predicting 85th percentile speeds with the latter two being used for tangent speed models on low speed 2-lane rural highways.

Unlike other research on operating speeds, Figueroa Medina and Tarko (*12)* developed a model which assessed the impacts of road features on operating speed choice and speed dispersion on tangent highways. Moreover, the study was also the first to develop an operating speed model using OLS regression which was applied to Panel Data (PD). The study found that increases in PSL and sight distance significantly increased operating speed. Interestingly, the study found that decreases PSLs and roadside object clearance both increased speed variability.

In other recent work Bassani et al. (*6)* attempted using a random effect model on panel data in order to take into account the hierarchical nature of the speed data collection process. The study found that transversal geometric characteristics such the number of travel lanes have more influence on operating speeds in an urban environment than longitudinal segment characteristics.

Dinh and Kubota (*13)* conducted a study on urban residential streets in Japan. The authors developed four models: two were for the operating speed in lanes one and two, and the remaining two models were for the speed deviation within each lane. The study found that street length, roadside object density and carriageway width all had statistically significant effects on speeds.

Eluru et al. (*14)* used data from urban roads in Montreal, Canada to model operating speeds. Two separate models were created—one for collectors and one for arterials. A fractional split model was used in the analysis so that the vehicles could be grouped by speed bins as opposed to modelling a single speed. The model would then generate probabilities instead of a single speed percentile. The study found that higher operating speeds were recorded at locations with biking facilities and sidewalks. One limitation of this study is that it did not control free flow conditions.

As already noted earlier and as evident from the literature review, only a few studies deal with modeling operating speeds on urban roads, especially on tangential segments. Moreover, few studies considered modelling speed variability concurrently while modeling mean or 85th percentile speeds.

3. DATA DESCRIPTION

3.1 Base Data

The data used in this paper was collected at 249 randomly selected (i.e. 126 arterial, 123 collector) tangential segments in urban roads in the City of Edmonton between years 2009 and 2013. The data was collected using the Vaisala Nu-Metrics Portable Traffic Analyzer NC200. The device is placed at the midpoint of each segment and uses build in sensors to detect, count, measure speeds and measure length of vehicles. The base data was reduced to include only free flow traffic using a two second headway. The reason a 2-second threshold was used in this study is related to the fact that the City of Edmonton recommends drivers to keep a 2-second headway during normal dry weather conditions. This threshold has also been used in previous studies within the city (*15-17*). In fact, in other research using the same dataset sensitivity analysis was performed to ensure that the congestion effects had indeed been omitted from the data. The dataset was filtered at several headways ranging between 2 seconds and 10 seconds, and models were developed for each case. In each of the cases, the results showed only slight change in the parameter estimates and no change in parameter significance indicating that congestion had already been eliminated when a 2-second threshold was used, and that filtering at higher headways does not seem necessary. For more information about the sensitivity analysis see (*4*). After filtering out congestion effects the average number of observations per site was 80752.4 vehicles. Additional variables representing general road features, roadside features, and on-road features were collected. The dataset also included the average vehicle length at a particular location which was used as a proxy of traffic composition. Descriptive statistics are shown in Table 1.

Table 1: Descriptive Statistics of Variables

	Variable Type*	Minimum	Maximum	Mean	Std. Deviation
Median Width (m)		0	10.4	2.89	7.76
Length (m)		43	1363	225.5	184.69
Road Width (m)		7	57	14.99	5.51
Total Blvd (m)		0	16	2.62	3.13
Access Density (per km)		0	103	16.21	18.75
Pole Density (per km)		0	115	33.19	16.9
Tree Density (per km)		0	203	82.1	51.14
Avg. Offset (m)		1	9	3.03	1.7
Posted Speed Limit (km/hr)		40	100	53.7	6.88
Avg. Vehicle Length (m)		5	8	5.43	0.39
One-Way	Binary	0	1	0.03	0.17
Pedestrian Crossing	Binary	0	1	0.04	0.21
Bus Stop	Binary	0	1	0.57	0.5
Service Rd	Binary	0	1	0.13	0.34
Roadside Hazard Rating	Categorical	1	7	4.23	1.25
Median Type	Categorical	1	6	4.55	1.41
End Treatment (NE)	Categorical	1	4	2.91	1.37
End Treatment (SW)	Categorical	1	4	2.88	1.36
Roadside Treatment	Categorical	1	4	3.11	0.75
Lanes	Categorical	1	7	3.16	1.37
Parking	Categorical	1	3	1.88	0.99
Sidewalk	Categorical	1	4	2.55	1.17
Tree Maturity	Categorical	1	3	1.69	0.82
Bike Route	Categorical	1	5	4.88	0.55

*Different levels for Categorical variables are discussed in the next few paragraphs. For binary variables "1" indicates the presence of the feature and "0" indicates its absence.

3.2 General Road Features

Five general road features were included in the analysis, these are i) segment length, ii) one-way, iii) pedestrian crossing, iv) PSL and v) end conditions of the segment. Segment length was measured from/to the center of an intersection or the beginning of a curve where the segment begun/ended. Whether a road was a one-way or not and the presence/absence of a pedestrian crossing facility were recorded as binary operators. Tangent segments are 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 of the tangent section) were defined. The four end conditions observed in the data are: signalized intersection, stop controlled intersection, curves and uncontrolled intersection.

3.3 Roadside Features

Roadside features include seven elements of the built environment directly adjacent to the tangent section. These elements measure the existence of different roadside features and the proximity of those features to the road as seen in Table 2.

Table 2: Roadside Features

Feature	Description
Sidewalks	1. Boulevard walk on both sides. 2. Boulevard walk on one side and monowalk on the other. 3. Monowalk on both sides. 4. No walk or boulevard on one side. A monolithic sidewalk is one which is connected to curb and gutter. It's typically poured 'monolithically' with the curb and gutter. A boulevard walk is one where there is a space between the curb and sidewalk. That space is usually some type of greenery which may or may not include trees.
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.
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.
Access Point Density	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.
Pole and Tree Density	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. The total number of trees on both sides of the road divided by the total length of road in kilometers was also included as a variable.
Average Object Offset	Average object offset is the average distance of all trees and poles from the face of curb.
Tree Maturity	Tree maturity was classified into three groups based on diameter: • Group 1 included mature trees with large diameter (around 30cm) on one side or both. • Group 2 comprised mixed tree age on one side, young trees (small diameter, around 15cm) on one side, and midsized or mixed on the other side, or midsized trees on both sides. • Group 3 comprised no trees, young trees (diameter around 5cm) on one side, or young trees on both sides.

3.4 On-Road Features

Six on-road features were identified: median type, road width, number of lanes, parking, on road bike markings, and the presence of a service road.

The median was divided into six categories: divided median, barrier median, raised median with or without trees, painted median, painted line, and no line. These were coded 1 to 6, respectively. Road width measured the asphalt width of the roadway in meters. Median width was not included in the road width variable.

The number of lanes was defined as the total number of travel lanes. Parking lanes were not counted as a lane but rather were included in the road width value and on street parking was noted. Three categories were defined for roadside parking: parking, off peak parking and no parking, coded as 1 to 3, respectively.

On-road bike markings were also considered, this variable was broken into five categories: (i) buffered bike lanes on both sides (ii) marked bike lane on one side and a buffered lane on the other (iii) marked bike lane on both sides, (iv) marked bike lane on one side of the road, and (v) no bike marking and sharrows on one side or both.

A service road is directly adjacent to a higher volume road (typically an arterial), which is used for local access. The presence of a service road was coded as a binary value.

3.5 Roadside Treatment

The models in this study used a roadside treatment 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 treatment was broken into four categories (i) downtown commercial, (ii) mixed high to medium density, (iii) mixed low density, and (iv) open urban. These ratings are intended to classify the general offset of buildings from the road and the intensity of use directly adjacent to the road. These classifications are meant to act as a generalized proxy for visual distractions and intensity of pedestrian traffic. Downtown commercial represents the highest density of buildings and the least amount of offset. 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. 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 as a landscaped area between a monolithic sidewalk and building. 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. Open urban has 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.

4. METHODOLOGY

4.1 Panel Data Approach

Ordinary Least Squares (OLS) regression is often used to develop speed prediction models. Despite their simplicity and popularity, OLS models suffer from a few drawbacks including the inability to model speed variability when developing speed prediction
models.

As means of addressing the limitations of OLS regression models, Figueroa Medina and Tarko (*12)* recommended the use of Panel Data (PD) when developing such models. Before proceeding with the model structure, it is worth noting that the use of panel data in this paper differs from traditional panel data use. In order to be able to analyse speed variability, this paper spreads data from different locations across speed percentiles rather than time which is typically the case when panel data is analysed in other fields such as medicine and economics.

In the structure recommended in (*12*), the data is arrayed in percentiles from the 5th percentile to the 95th percentile. Since speeds are normally distributed, 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 85th percentile speed V_{85}, is 1.036. This increases the degrees of freedom of the model since more data is available per location and, consequently, collinearity issues are less of a concern.

The PD also factors speed variation into the model. The first component of the equation 2 is 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. The model is developed using PD and the model parameters are estimated using OLS, hence, the name OLS-PD model.

$$V_{ip} = m_i + Z_p \times \sigma_i + \varepsilon = \sum_j a_j \times X_{ij} + \sum_k b_k \times (Z_p \times X_{ik}) + \varepsilon \quad [1]$$

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 equation, 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.

Since the data used in this paper included categorical variables, the GLM procedure in SAS v9.4 was used to estimate model parameters. A stepwise backwards elimination process was used to estimate the models. Three different models were estimated one including arterial and collector locations combined (A&C model) and two other models one for arterials only (A model) and one for collector roads only (C model).

4.2 Goodness of Fit

The goodness of fit of the models was measured using the *R*-squared test. As shown in Tables 3, the models were a good fit to the data with *R*-squared values greater than 0.60 for each of the models. During model development, multicollinearity between variables was also investigated. Variables that were clearly correlated were combined or one was dropped. For instance, Roadside Hazard Rating (*RHR*) variable was dropped from the models due to correlation with average object offset.

5. RESULTS AND DISCUSSION

Table 3 provides a summary of the variables with statistically significant effects on operating speeds and speed variability for all three models. The difference between the three models indicates that geometric features affecting operating speeds vary between road classifications. When comparing Arterial and Collector models, it was noticed that a number of variables have opposite effects on operating speeds such as: median width, road width, object density, object offset, PSL, and bus stop. The variation of statistically significant variables between the two models indicates that creating a single unified urban operating speed model might not be appropriate. In general, the Arterial model was more consistent with findings of highway models. This is to be expected, since arterials are designed for higher speeds and volume of traffic when compared to collectors. The speed variability was reduced as the road classification increased, with the *A&C* model showing lower speed variability on arterials compared to collectors.

5.1 End Treatment (boundary conditions)

The end treatments of a segment had statistically significant effects on reducing operating speeds in the *A&C* model. When compared to an intersection where a vehicle has the right-of-way, signalized intersection had the greatest impact on reducing speeds, followed by a stop controlled intersection and finally curves. In the separated models for arterial and collectors, end treatments did not have any statistically significant effects.

5.2 General Road Features

All models indicated that operating speeds increased with an increase in road length. Specifically, the *C* model shows that a 1kph increase in speed is observed with every 100 to 110m of addition length. The *A* model shows a 1kph increase for every additional 330 meters. Unlike segment length, one-way roads seemed to have lower operating speeds when compared to two-way roads. Similar findings were found by the Eluru et al. (*14)*. The results of the effects of posted speeds limits, based on the *A&C* and *A* Models, indicated that higher operating speeds are expected in areas with higher PSL. These results were again consistent with existing evidence from the literature. The *A&C* and *A* models also had a positive association between PSL and speed variability. This indicates that locations with higher PSL were also expected to have higher variability in operating speeds. It is worth noting here that the majority of collector roads had a PSL of 50kph, hence, despite the significance of the PSL variable in the C model, there was not much variability for the model to capture the true effects of the variable on operating speeds.

5.3 Roadside treatment

Roadside treatment was only found to be statistically significant in model *C*. Roadside treatment had statistically significant effects on both operating speeds and speed variability. Mixed low density areas experienced the highest operating speeds but the lowest speed variability. In contrast, Mixed high to medium density areas had the lowest operating speeds but highest speed variability. Lower operating speeds on mixed high to medium density areas are possibly due to the lower building offset on those segments as closer buildings limit the peripheral vision of drivers, which typically leads to lower operating speeds.

Table 3: Variables with Significant Effects on Operating Speed & Speed Variability

Operating Speed									
	***A&C* Model (R^2 = 0.78)**			***A* Model(R^2 = 0.84)**			***C* Model(R^2 = 0.77)**		
Parameter	**Est**	**S.E**	**p-val**	**Est**	**S.E**	**p-val**	**Est**	**S.E**	**p-val**
Intercept	33.09	1.626	<.0001	6.77	2.613	0.0097	49.79	2.477	<.0001
General Road Features									
Median Width (m)	0.38	0.015	<.0001	0.29	0.015	<.0001	-0.4	0.086	<.0001
Length(m)	0.0088	0.001	<.0001	0.003	0.001	<.0001	0.01	0.002	<.0001
One-way	-5.06	0.526	<.0001	-7.22	0.635	<.0001	-7.2	0.769	<.0001
PSL (km/hr)	0.22	0.018	<.0001	0.36	0.024	<.0001	-0.18	0.027	<.0001
Roadside Features									
Total Blvd				0.25	0.032	<.0001	0.13	0.05	0.0095
Access Density (Per km)	-0.04	0.005	<.0001	-0.16	0.011	<.0001	-0.03	0.005	<.0001
Pole Density (Per km)				-0.12	0.007	<.0001	0.15	0.01	<.0001
Tree Density (Per km)	-0.01	0.002	<.0001	-0.02	0.002	<.0001	0.01	0.003	0.0045
Avg. Object Offset	0.75	0.06	<.0001	0.82	0.075	<.0001	-0.29	0.085	0.0008
Walk1[a]	1	0.324	0.0021						
Walk2 [a]	-1.31	0.311	<.0001						
Walk3 [a]	-3.24	0.3	<.0001						
Roadside Treatment									
Mixed-High to Medium Density[c]							-8.287	1.011	<.0001
Mixed-Low Density[c]							2.807	0.69	<.0001
On-Road Features									
Road Width (m)				-0.24	0.027	<.0001	0.44	0.06	<.0001
Pedestrian Crossing							-1.99	0.489	<.0001
Bus Stop				0.79	0.242	0.0011	-1.03	0.223	<.0001
Service Rd							3.4	0.739	<.0001
Bike Route3 [b]	11.63	1.346	<.0001						
Bike Route4 [b]	-2.89	1.185	0.0147						
Traffic Composition									
Ave Vehicle Length (m)	1.02	0.229	<.0001	6.76	0.446	<.0001	-0.72	0.226	0.0015

p-val: P-value <0.05 indicates statistical significance at the 95% confidence level.

Table 3 Cont.: Variables with Significant Effects on Operating Speed and Speed Variability

	***A&C* Model**			***A* Model**			***C* Model**		
Parameter	**Est**	**S.E**	**p-val**	**Est**	**S.E**	**p-val**	**Est**	**S.E**	**p-val**
End Treatments									
NEEnd1	-1.490	0.222	<.0001						
NEEnd2	-4.940	0.439	<.0001						
NEEnd3	-1.202	0.359	0.0008						
NEEnd4	0.000	.	.						
SWEnd1	-4.373	0.249	<.0001						
SWEnd2	-2.661	0.330	<.0001						
SWEnd3	-2.183	0.390	<.0001						
SWEnd4	0	.	.						
Speed Variability									
PSL (km/hr)	0.05	0.016	0.002	0.06	0.017	0.0002			
One-way							-2.54	0.803	0.0016
Access Density	0.01	0.005	0.005	0.04	0.01	<.0001			
Tree Maturity 1	6.86	0.837	<.0001						
Tree Maturity 2	6.67	0.841	<.0001						
Tree Maturity 3	7.26	0.898	<.0001						
Road Width (m)							-0.14	0.051	0.0065
Avg Veh Length (m)				0.91	0.187	<.0001			
Road Class A	-0.86	0.222	0.0001						
Road Class C	0	.	.						
Road Class L									
Roadside 2							11.98	1.01	<.0001
Raodside 3							11.5	0.636	<.0001
Roadside 4							11.82	1.089	<.0001

a: relative to sidewalk type 4, b: relative to bike route type 5, c: relative to open urban area

5.4 Roadside Features

A number of roadside features were found to effect operating speeds and speed variability. Sidewalks were found to have statistically significant effects on speeds in the *A&C* model while boulevards were statistically significant in the *A* and *C* models. In the *A&C* model, boulevard walks on both sides were associated with the higher operating speeds, followed by any type of walk on one side, then boulevard walk on one side and monolithic walk on the other side. Mono-walk on both sides is correlated with the lower speeds. In general, both sidewalk and boulevard variables indicate that, as these features are moved away from roads, operating speeds increase.

All three models showed a negative correlation between access density and operating speeds. These findings are intuitive considering that increases in access density increase interruptions to traffic, hence, the reduction in operating speeds and mobility. The *A&C* and *A* models also show a positive association between access density and speed variability which is also intuitive considering that disruptions to traffic tend to increase the variability of speeds along a segment.

Significant effects were also observed in case of fixed objects and their offsets from the road, 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. Both models indicate that, as tree density increase, operating speeds are reduced. Likewise, they indicate that operating speeds are reduced as the objects become closer to the road. In the *A&C* model, speed variability also decreased with increases in tree density. Additionally, in the *A* model driving speeds were reduced as pole densities increased. In contrast, the *C* model showed that operating speeds increased as object density and their proximity to the road increase. It is worth noting here that collectors varied from residential roads to roads which had similar characteristics to arterials. For collectors which were surrounded by residential blocks, these roads had lower object density, hence the lower speeds observed on those low object density roads could be related to the residential nature of the surrounding environment.

5.5 On-Road Features

Medians were broken into two variables: median width and median type. Only the median width was statistically significant in the *A&C* and the *A* models where increases in median width were associated with in increases in operating speeds. This is consistent with the findings by Fitzpatrick et al. (*18)*.

Collector model had contrary findings, 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. Median on collectors are used more for community aesthetic rather than for strict engineering design. As a result, collector medians have more of a traffic calming effect.

Road widths were also found to be statistically significant in both the *A* and *C* models. In the *C* model, wider roads were correlated with higher speeds, while in the *A* model increases in road width were associated with reductions in operating speeds. This negative correlation on arterials may be down to the difference in design between older and newer arterials than actual road width. Businesses typically abut older arterials and have one lane of off peak parking on either side. In Edmonton, Arterials built since the 1970s have permanent parking bans on both sides and business parking is accommodated in parking lots. Hence, although road width dropped in new designs, more space is available due to new arterials banning parking.

Bus stops also had opposite effects on arterials compared to collectors. On arterials, presence of bus stops was associated with higher speeds. The opposite was true for collectors, where the presence of a bus stop reduced operating speeds. The difference 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 unlike collector locations which typically have a single travel lane in each direction. The fact that busses use separate travel lanes on arterials means that the influence of those busses on arterial roads could be lower.

Pedestrian crossings had a statistically significant impact on speed on collector roads, with locations where a pedestrian crossings facility is present having lower operating speeds, most likely due to drivers anticipating pedestrian activity on those segments.

The presence of bike lanes was associated with an increase in operating speeds in the *A&C* model. This finding is consistent with evidence from the literature *(19)* and could be a matter of drivers taking advantage of the extra road width, which is usually available on roads with biking facilities. A positive correlation was also observed between service roads and operating speeds on collectors. It is likely that service roads increase operating speeds as they operate in two ways: they control access and they create a wider field of view.

The average vehicle length, which acted as a proxy for traffic composition was significantly correlated to operating speed in all models. The *A&C* and *A* models a positive correlation was observed, while in the *C* model the correlation was negative. The difference here could be related to the difference in use and size between the two road types. 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.

5.6 Main Findings and Implications

Many inferences can be drawn from the results including several opportunities to reduce the operating speeds on road sections. In case of arterials, bringing traffic together by removing medians and narrowing travel lanes will result in lowering the operating speeds. For roadside treatments, the more objects (trees, poles, etc.) and the higher the access point density, the slower the operating speed. Moving biking lanes off the road, reducing boulevard areas, and moving pedestrians closer to the road all seem to have an impact on reducing operating speeds.

Several elements on collector roads can also be altered to reduce operating speeds. The basic elements, such as road width and length, can be reduced. Collectors with resident and business access are also more likely to have lower operating speeds. Further, speed reduction is also expected on roads with higher building density and lower building offset. The effects of medians on operating speeds on collectors is different from arterials. This could be a matter of medians having traffic calming effects on collectors.

When comparing speed variability on collectors and arterials, it is seen that on arterials there is less variability in speeds. Moreover, speed variability on collectors is correlated with different attributes compared to arterials. On arterials, increase in the number of access points, higher PSL, and increase in vehicle size all have statistically significant effects on speed variability. This is different from collectors, where lower speed variability is expected on one-way roads, wider roads, and less dense areas.

6. PARSIMONIOUS MODELS: DEVELOPMENT AND VALIDATION

Using the above data, parsimonious models were developed to predict operating speeds. A parsimonious model is one that accomplishes the desired level of prediction with as few predictor variables as possible. As a result, variables were dropped from the models if their effects on the response variable seemed to be marginal and the Akaike Information Criterion (AIC) of the model, a measure of the trade-off between the goodness of fit of the model and its complexity, was either unchanged or decreased after dropping the variable. This was done for all three models. Furthermore, model validation and testing were conducted using the GLMSELECT procedure in SAS. In this procedure the dataset was split into different portions, one portion was used to re-estimate the models while the other portion was used to verify the prediction capabilities of the model to select the most accurate model. Ten percent of the total sample size (i.e. data from 10% of the locations) was used as a test data. This portion of dataset was only used for model verification purposes and was not part of the model estimation process.

The procedure to develop parsimonious models decides on what effects are added or dropped and when to terminate the selection based on the average squared error (ASE) using the validation data. The effect in the current model whose removal yields the maximal decrease in the ASE statistic is dropped provided that this lowers the ASE value. The method terminates when dropping or adding any effect increases the AIC or the ASE statistic. The reduced and validated models are shown in table 4. Moreover, the table also shows the AIC statistics of the validated models, which is the minimum achievable value after applying the GLMSELECT procedure.

It is seen from the models that general road features seem to have the most significant effects on operating speeds on Arterials. This includes factors such as wider medians, longer segments both encouraging higher speed. In contrast to arterials, roadside objects and roadside treatment seem to have the most prevalent effects on collector operating speeds. This is reasonable considering that the roadside is typically highly populated on collectors and hence causes some distraction to drivers possibly affecting their speeds. Speed variability is also affected by roadside treatment on collector roads, indicating the importance of taking roadside environment into consideration when designing roads.

In case of the combined Arterial and Collector model, categorical variables such as the boundary conditions on the segment and the types of sidewalks on the segment seem to have highly significant impacts on operating speeds. These features are significant in the *A&C* model, even though there impacts on the individual A and C models were marginal. This could be due to low variability in those features within a certain road class (i.e. Certain types of sidewalks or boundary conditions might be more common on arterials while other types could more common on collectors).

Another important observation from the validated models is that fixed object density seems to have significant impacts on operating speeds on both arterials and collectors. Fixed objects such as poles and trees on the side of the road are an integral element to urban roads, despite that, they are not always considered in the design process. In fact, this finding highlights the importance of developing operating speed prediction models for urban tangent segments.

Table 4: Validated Prediction Models (Operating Speed Variables)

	A&C Model (AIC = 14960)			*A* Model (AIC = 6992)			*C* Model (AIC = 6863.5)		
Parameter	**Est**	**S.E**	**tVal**	**Est**	**S.E**	**tVal**	**Est**	**S.E**	**tVal**
Intercept	37.01	1.25	29.72	6.73	3.16	2.13	44.78	2.08	21.57
General Road Features									
Median Width (m)	0.38	0.02	22.72	0.30	0.02	16.90			
Length (m)	0.01	0.00	10.56	0.003	0.001	3.39			
One-way	-5.13	0.63	-8.13	-7.31	0.74	-9.86			
PSL (km/hr)				0.33	0.03	11.63	-0.14	0.03	-4.38
Roadside Features									
Total Blvd				0.22	0.04	5.80			
Access Density (Per km)	-0.04	0.01	-6.83	-0.17	0.01	-12.95			
Pole Density (Per km)	0.25	0.02	11.26	-0.11	0.01	-12.46	0.14	0.01	12.37
Tree Density (Per km)	-0.02	0.00	-7.19	-0.02	0.00	-6.77	0.01	0.003	2.84
Avg. Object Offset	0.76	0.07	10.62	0.88	0.09	10.00	-0.29	0.085	-3.37
Walk1	1.25	0.39	3.22						
Walk2	-1.07	0.37	-2.86						
Walk3	-2.91	0.36	-8.09						
Walk4	0.00	.	.						
Roadside 2							-6.06	1.10	-5.50
Roadside 3							3.15	0.70	4.50
Roadside 4							-6.06	1.10	-5.50
NEEnd1	-1.43	0.27	-5.39						
NEEnd2	-5.14	0.52	-9.83						
NEEnd3	-1.13	0.44	-2.58						
NEEnd4	0.00	.	.						
SWEnd1	-4.17	0.30	-14.08						
SWEnd2	-2.81	0.41	-6.82						
SWEnd3	-1.93	0.45	-4.27						
SWEnd4	0.00	.	.						
On-Road Features									
Road Width				-0.19	0.03	-5.90	0.38	0.06	6.76
Service Rd							4.00	0.88	4.54
Bike Route3				12.30	1.68	7.31			
Bike Route4				-2.43	1.38	-1.77			
Bike Route5				0.00	.	.			
Traffic Composition									
Avg. Veh Length (m)				6.92	0.54	12.76			

Table 4 Cont.: Validated Prediction Models (Speed Variability Variables)

	***A&C* Model**			***A* Model**			***C* Model**		
Parameter	**Est**	**S.E**	**tVal**	**Est**	**S.E**	**tVal**	**Est**	**S.E**	**tVal**
Tree Maturity 1	9.21	0.19	49.02						
Tree Maturity 2	8.84	0.26	34.55						
Tree Maturity 3	9.67	0.27	36.43						
Roadside 2							9.16	1.13	8.10
Roadside 3							9.78	0.15	63.21
Roadside 4							9.52	0.68	13.99

7. CONCLUSION AND RECOMMENDATIONS

The majority of existing operating speed models focused on rural two-lane highways with limited studies focusing on urban roads. Typically, urban models included only one feature (e.g. median treatments) or considered roads of a single land use category (e.g. 30 km/h residential roads). Only three models were found in the literature that analyzed the effects of all geometric features on speeds in urban areas (*6; 11; 14*). This paper expanded on previous research by using a much larger dataset that included significantly more variables. The paper also evaluated variables with impacts on speed variability. The findings from this paper should be valuable to designers and planners in their attempt to understand the relationship between operating speeds and several design factor. However, the research has a few limitations. One of those limitations is the inability to consider parking occupancy rates or pedestrian/cycling volumes. Unfortunately, data to consider such features was unavailable at the time of this study. Another limitation is that some variables were underrepresented (e.g. segments with vertical grades). This prevented the authors from understanding more about the effects of these variables on operating speeds. The lack of data about the lane position from which the speed data was collected could also be seen as a limitation of the research. Despite these limitations, the models developed in this study are recommended for predicting operating speed on urban roads. It is also recommended that the models are used to predict operating speeds in other regions which creates an opportunity for future research to test the transferability of the models.

ACKNOWLEDGEMENTS

This study was sponsored by NSERC Discovery Grant. The authors would like to thank the City of Edmonton and Office of Traffic Safety for providing the data to conduct this study.

REFERENCES

[1] Hassan, Y., T. Sayed, and V. Tabernero. Establishing practical approach for design consistency evaluation. *Journal of Transportation Engineering*, Vol. 127, No. 4, 2001, pp. 295-302.

[2] Polus, A., K. Fitzpatrick, and D. Fambro. Predicting operating speeds on tangent sections of two-lane rural highways. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1737, 2000, pp. 50-57.

[3] Watson Jr, D. C., A. Al-Kaisy, and N. D. Anderson. Examining the effect of speed, roadside features, and roadway geometry on crash experience along a rural corridor. *Journal of Modern Transportation,* Vol. 22, No. 2, 2014, pp. 84-95.

[4] Gargoum, S. A., K. El-Basyouny, and A. Kim. Towards setting credible speed limits: Identifying factors that affect driver compliance on urban roads. *Accident Analysis & Prevention,* Vol. 95, 2016, pp. 138-148.

[5] Fitzpatrick, K., P. Carlson, M. Brewer, and M. Wooldridge. Design factors that affect driver speed on suburban streets. *Transportation Research Record: Journal of the Transportation Research Board,* No. 1751, 2001, pp. 18-25.

[6] Bassani, M., D. Dalmazzo, G. Marinelli, and C. Cirillo. The effects of road geometrics and traffic regulations on driver-preferred speeds in northern Italy. An exploratory analysis. *Transportation research part F: traffic psychology and behaviour,* Vol. 25, 2014, pp. 10-26.

[7] Esposito, T., R. Mauro, F. Russo, and G. Dell'Acqua. Speed prediction models for sustainable road safety management. *Procedia-Social and Behavioral Sciences,* Vol. 20, 2011, pp. 568-576.

[8] Hassan, Y., and M. Sarhan. Modeling Operating Speed: Synthesis Report. Chapter 1: Introduction. *Transportation Research E-Circular,* No. E-C151, 2011.

[9] Ali, A. T., A. Flannery, and M. M. Venigalla. Prediction models for free flow speed on urban streets.In *Transportation Research Board 86th Annual Meeting*, 2007.

[10] Fitzpatrick, K., S.-P. Miaou, M. Brewer, P. Carlson, and M. D. Wooldridge. Exploration of the relationships between operating speed and roadway features on tangent sections. *Journal of Transportation Engineering,* Vol. 131, No. 4, 2005, pp. 261-269.

[11] Wang, J., K. Dixon, H. Li, and M. Hunter. Operating-speed model for low-speed urban tangent streets based on in-vehicle global positioning system data. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1961, 2006, pp. 24-33.

[12] Figueroa Medina, A., and A. Tarko. Speed factors on two-lane rural highways in free-flow conditions. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1912, 2005, pp. 39-46.

[13] Dinh, D. D., and H. Kubota. Profile-speed data-based models to estimate operating speeds for urban residential streets with a 30km/h speed limit. *IATSS research,* Vol. 36, No. 2, 2013, pp. 115-122.

[14] Eluru, N., V. Chakour, M. Chamberlain, and L. F. Miranda-Moreno. Modeling vehicle operating speed on urban roads in Montreal: A panel mixed ordered probit fractional split model. *Accident Analysis & Prevention,* Vol. 59, 2013, pp. 125-134.

[15] Islam, M. T., K. El-Basyouny, and S. E. Ibrahim. The Impact of Lowered Residential Speed Limits in the City of Edmonton.In *Transportation Research Board 92nd Annual Meeting*, 2013.

[16] Islam, M. T., and K. El-Basyouny. An integrated speed management plan to reduce vehicle speeds in residential areas: Implementation and evaluation of the Silverberry Action Plan. *Journal of safety research*, Vol. 45, 2013, pp. 85-93.

[17] Gargoum, S., and K. El-Basyouny. Analyzing Driver Compliance to Speed Limits Using Logistic Regression.In *Transportation Research Board 94th Annual Meeting*, 2015.

[18] Fitzpatrick, K., P. Carlson, M. Brewer, and M. D. Wooldridge. Design speed, operating speed, and posted speed limit practices.In *82nd Annual Meeting of the Transportation Research Board, Washington, DC*, 2003.