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# Towards Setting Credible Speed Limits: Identifying Factors that Affect Driver Compliance on Urban Roads

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**Abstract**

Road geometry, vehicle characteristics, and weather conditions are all factors that impact a driver's perception of a safe or credible speed and, consequently, the driver's decision on whether or not to comply with the posted speed limit. In fact, the role a road's environment plays in a driver's perception of a credible speed limit is a topic that has attracted the interest of many researchers in recent years. Despite that, not many studies have considered using empirical data to investigate what features of the road environment influence a driver's compliance choice. This paper aims to address this matter by exploring the relationships between features of the road surroundings (geometric, temporal factors, and weather conditions) and driver compliance with speed limits. The paper uses data from almost 600 different urban roads in the city of Edmonton, at which over 35 million vehicle spot speeds were collected. Compliance was represented using a categorical ordered response variable, and mixed-effects-logistic-regression models were fitted. Two different models were built, one for arterials and another for collector roads. In general, the findings show that the more restricted drivers become, particularly on arterials, the more likely drivers are to comply with speed limits; potential restrictions include on-street parking and the absence of lateral shoulders. Furthermore, higher traffic activity during peak hours, and presumably on shoulder weekdays, both increase the likelihood of compliance on arterials. Similarly, posted speed limits and traffic volume are both positively correlated with compliance on both arterial and collector roads. The findings of this research provide evidence of the existence of an empirical relationship between road features and compliance, highlighting the importance of setting credible speed limits on roads and the possibility of achieving higher compliance rates through modifications to the road environment.

**Keywords**

Compliance; Speed Limit Credibility; Roadway Design Factors; Mixed Models Logistic Regression; Generalized Linear Mixed Models; Credible Speed Limits.

## 1. Introduction

Speeding is a major issue on roads all around the world, causing substantial damage and loss of life. Transport Canada reported that, in 2011, almost a third of fatalities and a fifth of serious injuries were speed-related (Road Safety Canada Consulting, 2011). Similarly, statistics from the US show that in 2012, 30% of road fatalities were speed-related (NHTSA, 2012). In addition to increasing the severity of collisions, speed has also been found to increase the risk of being involved in a crash (Aarts and Van Schagen, 2006). Despite that, drivers are still reluctant to comply with speed limits; statistics show that speed limit violations reach levels of 40% to 50% on some roads (OECD/ECMT, 2006). This percentage is highly discouraging, particularly when considering that perfect compliance to speed limits could see fatalities and injuries drop by 38% and 21%, respectively (Elvik and Amundsen, 2000).

In response to high violation rates, several speed management countermeasures have been considered. However, not much has been done to understand what factors actually encourage drivers to violate or comply with posted speed limits (PSL) on a certain roadway. A European review on speed management found that, in addition to the utility (e.g., travel time savings, thrill-seeking) and the disutility (e.g., sanctions, accident risk) associated with non-compliance, the "reasonableness" of a speed limit is also one of the most important factors in determining the degree of compliance to a speed limit (OECD/ECMT, 2006). In order to assess how reasonable the speed limit set on a certain road is, drivers usually integrate other factors related to the characteristics of a road and its immediate surroundings in their assessment. Based on this assessment, drivers might decide that the speed limit on a certain road is inappropriate or too low and not worthy of complying with.

According to Kanellaidis *et al.* (1995) speed limits being unrealistic is a key reason why drivers violate speed limits. This has led many researchers to study factors influencing driver perception of what is considered an appropriate speed at a certain location, and how speed limits should be set to account for road environment and become more credible (van Schagen *et al.*, 2004, Goldenbeld and van Schagen, 2007, Ivan *et al.*, 2009).

The concept of credibility has also led transport agencies around the world to recommend that speed limits are set while taking into account the road environment. In New Zealand, for instance, the Ministry of Transport acknowledges that setting speed limits must be done in a manner that is consistent with the level of the roadside development and the function of the road; moreover, the ministry also recommends that road geometry be considered as a secondary factor when setting a speed limit (LTSA, 2003). These guidelines have been put into practice and were found to have significant effects vehicle speeds as shown in the study by Charlton et. al, (2010). In that study, traffic management features were used create self-explaining roads and the study found significant reduction in vehicle speeds on local roads and increased homogeneity of speeds on both local and collector roads.

In one of the earliest studies that addressed the topic of speed limit credibility, Wilmot and Khanal (1999) mention that road geometric characteristics, land use and weather conditions all play a role in driver perception of a safe speed limit at a certain location. Moreover, Aarts *et al.* (2009) also integrated information about road design, road image, traffic characteristics and behavioural attributes into their algorithm, which was developed to assess the safety and credibility of a speed limit. Factors affecting compliance choice could also be extended to include vehicle characteristics and driver personality traits, since these factors have been found to affect speed choice.

Although driver judgment of an appropriate speed limit is highly subjective, designers and engineers should still work on increasing the harmony between the road environment and the Posted Speed Limit (PSL), in order to reduce the population of drivers doubting the credibility of a speed limit and, hence, increase compliance rates. That being said, creating this harmony between the road environment and PSL can only be achieved when the specific factors that influence compliance choice are identified and their effects are understood using empirical data from the field.

This paper attempts to address this matter using data collected at urban roads in the city of Edmonton, Canada. The data is used to develop ordered mixed-effects-logistic-regression models where driver compliance to speed limits is regressed on features of the road, climate and vehicles. The main aim of the analysis performed in this paper is to explore the effects of different factors, including features of the road environment, on drivers abiding to or violating speed limits, thereby providing design experts and enforcement officials with valuable information that will assist them in future planning and decision-making related to setting credible speed limits. As in case of the study by Goldenbeld and van Schagen (2007), this paper aims to bring the concept of credible speed limits into practice by identifying the specific factors that affect driver compliance.

The current study contributes to the existing literature on speed limit credibility in that it:

(i) Analyzes empirical data from the field, as opposed to questionnaire data, which was used in the only other study that attempted to operationalize the concept of credible speed limits by Goldenbeld and van Schagen (2007). In fact, Goldenbeld and van Schagen (2007) actually called for empirical analysis to validate the findings of their research.

(ii) Analyzes the effects of the road and roadside environment on actual driver compliance, not perceived safe speed, speed choice or preferred speed.

(iii) Considers the effects of a variety of different factors on compliance including the effects of dynamic factors, such as peak/off-peak time of day and weather conditions.

## 2. Previous Work

As already indicated, the majority of existing research, which has assessed the relationships between speed and features of the road environment, road design, traffic characteristics and climate conditions, has investigated the effects of those variables on speed choice, speed preference, perceived safe speed or in some cases speed variance. However, not many studies have assessed the impacts of those features on compliance to speed limits.

A common factor that has been considered in many studies is the posted speed limit (PSL). Fitzpatrick *et al.* (2001) developed linear regression models to assess factors affecting operating speeds on straight and curved suburban arterial road segments in Texas. The study found PSL to have the most significant effects on speeds. Similarly, Fitzpatrick *et al.* (2005) used data from different regions of the US to study the effects of different road features on operating speeds of tangent sections, using data from different regions of the US, and found PSL to be the most significant predictor of operating speed. In fact, the linear regression models developed showed that PSL was the only variable with statistically significant effects on speed. Aljanahi *et al.* (1999) and Finch *et al.* (1994) also found a significant relationship between speed and PSL, showing that reduction in PSLs is associated with reduction in observed speeds.

As part of the *SaCredSpeed* algorithm developed by Aarts *et al.* (2009) to assess the credibility of speed limits using general safety principles, the authors provided a summary of factors that they thought had an influence on driving speed and on which the credibility of the speed limit could be based. Among those variables were the presence of pedestrian facility (decelerator), the presence of a cycling facility (decelerator), the presence of on-street parking (decelerator), increased number of lanes (accelerator), increased road and lane widths (accelerator) and the higher density of the road environment (decelerator), which was defined in terms of dense vegetation or built-up areas.

In a study assessing the credibility of 80kph speed limits on rural roads in the Netherlands, Goldenbeld and van Schagen (2007) used questionnaire data, asking respondents about their preferred speed and their perceived safe speed on a selection of rural roads. The authors developed an Analysis of Covariance (ANCOVA) model to relate driver speed choice to characteristics of the road and its environment as well as the effects of person and personality characteristics. The study found that the absence of a horizontal alignment, the increase in sight distance and clarity of the situation (visibility) and the absence of buildings at the roadside all resulted in higher speed preference and higher perception of a safe speed. Moreover, the paper also found that perception of safe speeds also increased with the absence of trees and increases in road width. In terms of the size of the effects, the study found that the horizontal curves and sight distance had the strongest effects on speed preference.

Although not in the context of speed limit credibility, other works assessing the factors affecting speed choice also highlight the importance of road design and geometry. According to Várhelyi (1997), the significance of the effects road design has on speed choice is even greater than that of the PSL. Likewise, Quimby *et al.* (1999) concluded that site characteristics had the largest influence on driver speeds.

In a study using speed data recorded on curved road segments in Australia, McLean (1981) developed a regression model to predict speeds on horizontal curves. The study found that attributes of horizontal curves (e.g., radius of curve and degree of curvature) had major effects on driver speed choice. Similarly, O'Flaherty and Coombe (1971) also reached similar conclusions. In contrary, Fildes *et al.* (1991) did not find significant difference in speed choice when comparing curved and straight segments. In a paper assessing the effects of road geometric features on speeds on two-lane highways, Yagar and Van Aerde (1983) used data from Ontario, Canada, to develop a multiple linear regression model. The study found that road curvature, along with the addition of a lane, had no statistically significant effects on speeds. Lane width and vertical grade, however, were found to be statistically significant, with a percent increase in upgrade predicted to reduce speeds by 2kph, and vice versa (i.e., a percent decrease in grade is predicted to increase speeds by 2kph). Figueroa Medina and Tarko (2005), developed a panel data ordinary least squares (OLS) model using data from two-lane rural highway segments in Indiana, US. Statistically significant variables affecting speeds on tangential road segments included highway grade, pavement width and shoulder width (Duncan, 1974).

Roadside features and road setting are also variables believed to impact driver speed choice. Using data from 250 roadway segments in Connecticut, US, Marshall *et al.* (2008) used analysis of variance (ANOVA) to assess the relationship between a number of road features and vehicle speeds. The study found that roadway type, land use, building setback and presence of on-street parking all had statistically significant effects on mean vehicle speeds. In the case of roadway type, street roadways (roads within an urban environment) were found to experience a speed reduction of 1.5mph when compared to highways (roads with a rural surrounding). Moreover, locations with smaller building setback and a presence of on-street parking were both associated with drops in mean speeds.

The effects of land use on speed were also measured in (Galin, 1981). Using data from Australia, the paper developed regression models to assess the impacts of several factors on the $85^{th}$ and $95^{th}$ percentile speeds. The paper found that speeds observed in low-density residential areas were significantly lower than those observed on roads in similar areas of agricultural terrain. The difference in speed was quantified to be at least 10kph. In another study conducted in the Netherlands, Rienstra and Rietveld (1996) concluded that whether a roadway is at an urban built-up area or a rural highway plays an important effect on compliance by affecting violation margins. The paper used survey data as part of the analysis. Similarly, Giles (2004) found that vehicle speeds in metropolitan areas in Western Australia were relatively lower than those in rural areas; it is worth noting that the study did account for differences in speed limits.

The effects of temporal and climate factors on speed choice have also been assessed in a number of studies. One study by Giles (2003) looked at the effects of time of day, day of week, and weather conditions, and found that regardless of the PSL, these factors do have an effect on driver speed choice. Galin (1981) found that weather conditions had significant effects on speed choice; in this paper it was found that dry and fine weather encouraged significantly higher speeds when compared to wet and cloudy conditions. The effects of time of day on speed limit violations was also assessed by Nouvier (1990) using data from France. The study found that non-compliance was more common in the early morning compared to midday. Similarly, ONISR (2005) also found that more violations were observed at night compared to daytime.

Vehicle characteristics, such as vehicle class and even vehicle age, also impact speed choice. Wasielewski (1984) found that drivers of heavy vehicles chose a higher speed than those driving passenger cars, while Giles (2004) reached similar conclusions, observing that increases in vehicle length were associated with increased speeds. Studies have also found that newer vehicles seem to be driven at higher speeds than older ones (Wasielewski, 1984, Fildes *et al.*, 1991).

Speed choice is also influenced by driver characteristics, such as personality traits (e.g., high confidence in skills or thrill-seeking), driver age (Fildes *et al.*, 1991, Walton and Bathurst, 1998, Goldenbeld and van Schagen, 2007) and driver gender, (Laapotti *et al.*, 2003, Consortium, 2004). With that being said, it is worth noting that these factors could not be considered in this study due to data limitations.

In summary, there is no doubt that speed choice and the perception of a safe speed are affected by a range of different attributes of roads, vehicles and climate. What is not as clear, however, is the relationship between those factors and actual compliance to speed limits. Analyzing this relationship is necessary to bring the concept of setting credible speed limits into practice.

## 3. Data Description

### *3.1 Dataset Description*

The speed data used in this study was collected by the City of Edmonton in speed surveys conducted across the city over a period of five years. The city of Edmonton is the capital of the province of Alberta in Western Canada and is home to around 800,000 people (COE, 2015). Roads in the city are designed in accordance with Transportation Association Canada (TAC) standards (City of Edmonton, 2012).

The instrument used by the City for data collection is the Vaisala Nu-Metrics Portable Traffic Analyzer NC200, shown in Figures 1 and 2 (Coral Sales Company, 2016). These devices have built-in sensors through which they detect, count, classify, and measure vehicular speeds. Installing these devices on the road is simple and they are hardly visible to road users.

**Figure 1: Vaisala Nu-Metrics Traffic Analyzer NC200**

**Figure 2: NC200 Analyzer in Field**

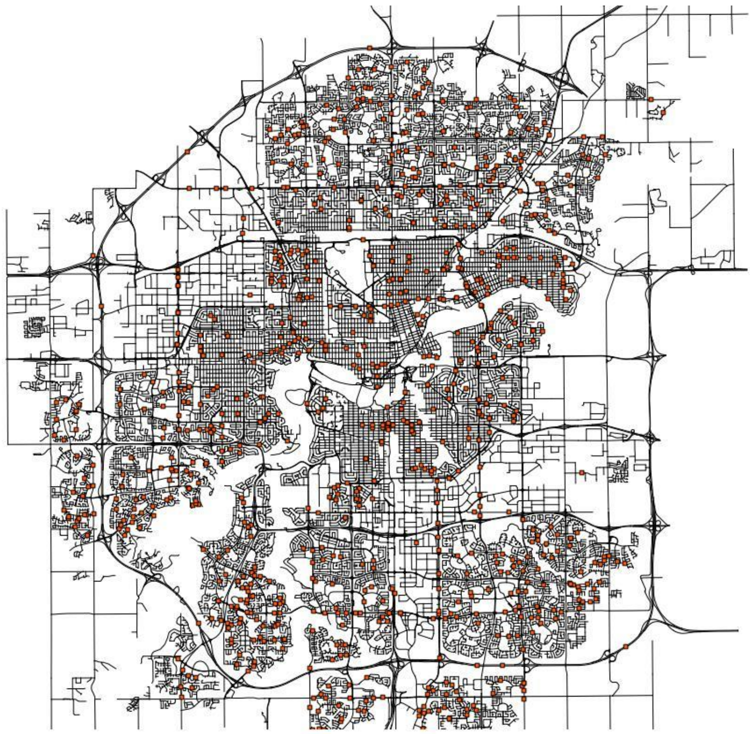

**Figure 3: Speed Survey Locations in the City of Edmonton**

The data included in the analysis was randomly collected from almost 600 different road segments across the city, as seen in Figure 3, between April 2009 and October 2013; multiple visits were made to each location and several observations were collected on every visit. The duration of the data collection period per visit varies. The City of Edmonton's visits to a speed survey location could range from three days up to about a week (i.e., the Vaisala Nu-Metrics Portable Traffic Analyzer NC200 is placed at a certain location for up to 7-8 days and data is collected 24 hours per day).

Processing and recoding the raw data yielded more than 35 million cases, which were considered in the analysis. In order to develop different models for arterial and collector roads, the dataset was divided up based on road class. The descriptive statistics of the data for arterials and collectors are shown in Tables 2 and 3 respectively. It is worth noting here that the reason different models were developed for arterials and collectors is that these different road classes typically differ significantly in terms of the amount of access provided, speed choice and possibly compliance choice. As a result, it was decided that developing two separate models could provide more insight into factors affecting compliance on roads of different classes.

## *3.2 Data Processing*

### *3.2.1 Free-flow Conditions*

Before analyzing the data, it was important to exclude vehicles experiencing traffic congestion from the dataset. This had to be done for two reasons: i) to avoid confusing actual compliance to speed with vehicles travelling in congested traffic conditions, and ii) to omit the resulting correlation between the speeds of vehicles in congested traffic. Vogel (2002) found that this correlation could confound the estimates of the factors considered in the analysis.

The threshold used to separate congestion conditions from non-congested conditions was a time headway of two seconds, and hence, vehicles having a recorded headway of less than two seconds were omitted from the dataset. It is worth mentioning that previous studies have used a wide range of thresholds to separate congested and uncongested conditions; 2 seconds (Islam and El-Basyouny, 2013), 3 seconds (Pasanen and Salmivaara, 1993), 4 seconds (Hauer *et al.*, 1982), 5 seconds (Misaghi and Hassan, 2005). 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 (Islam and El-Basyouny, 2013, Islam *et al.*, 2013, Gargoum and El-Basyouny, 2015). In addition to considering the 2-second threshold, each dataset was also filtered at higher thresholds, and a sensitivity analysis was performed to ensure that the congestion effects had indeed been omitted from the dataset.

The dataset was filtered at several headways ranging between 2 seconds and 10 seconds, and a generalized linear mixed model with a binary logit link function was run for each case. In each of the cases, the results show that only a slight change in the parameter estimates was present (not shown in the paper). This shows that the effects of the vehicles experiencing congestion had already been eliminated when a 2-second threshold was used, and that filtering at higher headways does not seem necessary.

The changes in the coefficient estimates between 2, 5 and 10 seconds was hardly recognizable. As for the changes in variable significance, although there was a marginal change in *p-values*, the significance of the variables did not change in any of the cases. In other words, variables that are significant at the 5% significance level remain significant in all three models, while insignificant variables remain insignificant regardless of the model used. These observations are valid for both arterial and collector roads.

#### *3.2.2 Compliance Categories*

The dependent variable used in the models developed in this paper was the driver compliance to speed limits. Since the raw data of the speed survey only contain vehicle speeds, the compliance of each vehicle to the speed limit had to be calculated by finding the difference between the vehicle's recorded speed and the posted speed limit at the survey location. Unlike in the case of the sensitivity analysis, which was solely exploratory, compliance was represented using an ordinal categorical variable, by which five different categories were defined.

(1) Travelling at speeds less than or equal to the PSL (Compliant).

(2) Exceeding PSL by no more than 5kph.

(3) Exceeding PSL by more than 5kph but no more than 10kph.

(4) Exceeding PSL by more than 10kph but less than 20kph.

(5) Exceeding PSL by 20kph or more.

The reason the compliance was divided into different categories was to help the model differentiate between vehicles violating speed limits by different margins. For instance, a vehicle driving at 61kph on a road with a PSL of 60kph should not be in the same category as a vehicle doing 100kph on the same road. Moreover, the City of Edmonton specifies certain thresholds (typically 10kph or 15kph) over the speed limit at which a violation is recorded against a driver, and a ticket is issued. The independent variables considered in the analysis will be discussed next, but first it is important to point out that human factors, such as age and gender, and vehicle performance characteristics, such as engine size, were not included in the analysis due to dataset limitations. Furthermore, it is important to note that after estimating the correlation matrix, no high or even moderate correlation was found between any of the independent variables. In fact, the majority of the correlation coefficients ranged from low to non-existent (<0.1). Most of the independent variables considered in the analysis were selected because they were found to affect speed choice or safe speed perception in previous research. It is worth noting that enforcement activity was not considered in the analysis. The main reason here is that, due to the length of the study period, data was not available for all locations. With that being said, the random effects parameters included in the models should take into account any variation in compliance rates due to enforcement.

### *3.2.3 Road Type and Classification*

The effects of land use on compliance were accounted for in the analysis. In total, six different types of land use were considered, including residential, industrial, agricultural, commercial, direct control and urban service areas. The dataset for collector roads only included residential and industrial areas; whereas, arterials were found in all four remaining categories. In addition to land use, the posted speed limits (PSL) at each road segment were also included in the model.

### *3.2.4 Geographic and Design Factors*

Geographic and design features at each site were collected manually using Google Street View images, which were available for all locations considered in the analysis (views from multiple years were compared to ensure that the feature of interest did not change). Most of those features were represented using binary variables, where "1" represents the presence and "0" represents the absence of that attribute. These features included the horizontal alignment (HA) of the road segment (0 for non-curved and 1 for curved), the vertical alignment (VA) of the road, whether the two approaches of the road segment were physically separated or not, and the presence or absence of shoulders, bus stops, and bike lane markings on the road segments. It is worth noting here that, since information about the degree of curvature was not available, a road segment was considered as curved or non-curved based on visual inspection from a driver's point of view (i.e., curvature had to be apparent to a driver in order for the segment to be considered curved).

For other design features, the variables were non-binary representations, such as street parking, where three different variables were used (0 for no parking, 1 for one-sided parking and 2 for two-sided parking). For each site, the number of lanes per direction was also recorded. Moreover, the vehicles were classified according to their length. The length classification followed was that of the Traffic Monitoring Guide of the U.S. Federal Highway Administration (FHWA, 2001) shown in Table 1.

**Table 1 Vehicle Classification Based on Length (FHWA, 2001)**

| Classification | Lower Length Bound (>) | Upper Length Bound (≤) |
|---|---|---|
| Passenger Vehicles | 0 | 3.96 |
| Single Unit Trucks | 3.96 | 10.67 |
| Combination Trucks | 10.67 | 18.59 |
| Multi-Trailer Trucks | 18.59 | 36.58 |

### *3.2.5 Temporal and Climate Factors*

In order to give some weight to climate conditions, weather information for the each of the data points was determined. This information was obtained by matching the exact time (to the nearest hour) and date at which the data point was recorded with the exact temperature, wind speed, and visibility at that time. The weather conditions at each data point were extracted from hourly weather records of the City of Edmonton maintained by Environment Canada.

Temporal data was recorded as the exact day of the week on which the vehicle's speed was recorded, as well as whether or not it was during peak (7:30–9:00AM and 4:00–5:30PM) or non-peak hours. Moreover, whether or not the day of week was a shoulder day (Monday or Friday) was also considered as a factor, with shoulder days given a value of "1." Seasonal factors were also investigated; due to the severe winters in Edmonton, the year was divided into three seasons only, with winter months being from December to April, summer months running from May to August and fall being from September to November. The three seasons were coded 1, 2 and 3 respectively.

### *3.2.6 Volume Measure*

In order to integrate a measure of traffic flow into the models, the number of vehicles per hour observed at each location during the data collection period (volume-per-hour-per-location) was computed. This was done for all hours included in the analysis, and the average volume per hour was then included as an independent variable in both the arterial and collector models.

**Table 2: Descriptive Statistics for Data Collected at Arterial Roads**

| Descriptive Statistics For Arterials | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Minimum** | **Maximum** | **Mean** | **Std. Deviation** | **Median** | **Mode** | **Percentiles** | | |
| **Response** | | | | | | | **25** | **50** | **75** |
| Compliance | 1 | 5 | 2.1337 | 1.26042 | 2 | 1 | 1 | 2 | 3 |
| **Vehicular Factors** | | | | | | | | | |
| Veh Class[d] | 1 | 4 | 1.93 | 0.363 | 2 | 2 | 2 | 2 | 2 |
| **Environmental Factors** | | | | | | | | | |
| Temp (°C) | -13.5 | 33.6 | 11.666 | 8.4222 | 12.3 | 13.6 | 5.9 | 12.3 | 17.9 |
| Wind Speed (kph) | 0 | 59 | 14.47 | 8.557 | 13 | 9 | 8 | 13 | 19 |
| Visibility (km) | 0 | 80.5 | 22.564 | 4.9123 | 24.1 | 24.1 | 24.1 | 24.1 | 24.1 |
| Season[a] | 1 | 3 | 2.66 | 0.503 | 3 | 3 | 2 | 3 | 3 |
| **Temporal Factors** | | | | | | | | | |
| Shoulder Day[b] | 0 | 1 | 0.32 | 0.465 | 0 | 0 | 0 | 0 | 1 |
| Peak/Off-Peak | 0 | 1 | 0.15 | 0.354 | 0 | 0 | 0 | 0 | 0 |
| **Design Factors** | | | | | | | | | |
| Lanes | 1 | 4 | 2.34 | 0.658 | 2 | 2 | 2 | 2 | 3 |
| Horizontal Alignment | 0 | 1 | 0.33 | 0.469 | 0 | 0 | 0 | 0 | 1 |
| Median | 0 | 1 | 0.81 | 0.394 | 1 | 1 | 1 | 1 | 1 |
| Vertical Alignment | 0 | 1 | 0.05 | 0.211 | 0 | 0 | 0 | 0 | 0 |
| Parking[c] | 0 | 2 | 0.07 | 0.348 | 0 | 0 | 0 | 0 | 0 |
| Shoulder | 0 | 1 | 0.12 | 0.33 | 0 | 0 | 0 | 0 | 0 |
| Ped Crossing | 0 | 1 | 0.06 | 0.237 | 0 | 0 | 0 | 0 | 0 |
| Bus Stop | 0 | 1 | 0.57 | 0.494 | 1 | 1 | 0 | 1 | 1 |
| PSL | 50 | 100 | 60.03 | 6.871 | 60 | 60 | 60 | 60 | 60 |
| **Exposure Measure** | | | | | | | | | |
| Volume | 1 | 21711 | 1473.06 | 1401.685 | 1153 | 2322 | 662 | 1153 | 2022 |
| **Land Use** | | | | | | | | | |
| Commercial | 0 | 1 | 0.66 | 0.472 | 1 | 1 | 0 | 1 | 1 |
| Agricultural | 0 | 1 | 0.06 | 0.23 | 0 | 0 | 0 | 0 | 0 |
| Urban Services | 0 | 1 | 0.02 | 0.122 | 0 | 0 | 0 | 0 | 0 |
| Direct Control | 0 | 1 | 0.26 | 0.441 | 0 | 0 | 0 | 0 | 1 |

[a] Season: Winter = 1, Summer = 2, Fall = 3.
[b] Shoulder Day: Monday/Friday = 1, Other = 0.
[c] Parking: No Parking = 0, One-Sided = 1, Two-Sided = 2
[d]Passenger Vehicles = 1, Single Unit Trucks =2, Combination Trucks = 3, Multi-Trailer Trucks = 4

**Table 3: Descriptive Statistics for Data Collected at Collector Roads**

| Descriptive Statistics For Collectors | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Minimum** | **Maximum** | **Mean** | **Std. Deviation** | **Median** | **Mode** | **Percentiles** | | |
| **Response** | | | | | | | **25** | **50** | **75** |
| Compliance | 1 | 5 | 2.1077 | 1.28427 | 2 | 1 | 1 | 2 | 3 |
| **Vehicular Factors** | | | | | | | | | |
| Veh Class[d] | 1 | 4 | 1.91 | 0.386 | 2 | 2 | 2 | 2 | 2 |
| **Environmental Factors** | | | | | | | | | |
| Temp (°C) | -13.5 | 33.6 | 12.659 | 7.7007 | 13.7 | 13.7 | 8.2 | 13.7 | 18.3 |
| Wind Speed (kph) | 0 | 59 | 15.39 | 9.085 | 14 | 9 | 9 | 14 | 20 |
| Visibility (km) | 0 | 80.5 | 19.791 | 6.6942 | 24.1 | 24.1 | 10 | 24.1 | 24.1 |
| Season[a] | 1 | 3 | 2.38 | 0.531 | 2 | 2 | 2 | 2 | 3 |
| **Temporal Factors** | | | | | | | | | |
| Shoulder Day[b] | 0 | 1 | 0.28 | 0.448 | 0 | 0 | 0 | 0 | 1 |
| Peak/Off-Peak | 0 | 1 | 0.18 | 0.382 | 0 | 0 | 0 | 0 | 0 |
| **Design Factors** | | | | | | | | | |
| Lanes | 1 | 3 | 1.16 | 0.378 | 1 | 1 | 1 | 1 | 1 |
| Horizontal Alignment | 0 | 1 | 0.47 | 0.499 | 0 | 0 | 0 | 0 | 1 |
| Median | 0 | 1 | 0.11 | 0.312 | 0 | 0 | 0 | 0 | 0 |
| Vertical Alignment | 0 | 1 | 0.001 | 0.051 | 0 | 0 | 0 | 0 | 0 |
| Parking[c] | 0 | 2 | 1.6 | 0.72 | 2 | 2 | 1 | 2 | 2 |
| Shoulder | 0 | 1 | 0.03 | 0.157 | 0 | 0 | 0 | 0 | 0 |
| Ped Crossing | 0 | 1 | 0.2 | 0.397 | 0 | 0 | 0 | 0 | 0 |
| Bus Stop | 0 | 1 | 0.62 | 0.485 | 1 | 1 | 0 | 1 | 1 |
| Bike Lane | 0 | 1 | 0.13 | 0.334 | 0 | 0 | 0 | 0 | 0 |
| PSL | 30 | 80 | 49.79 | 2.779 | 50 | 50 | 50 | 50 | 50 |
| **Exposure Measure** | | | | | | | | | |
| Volume | 1 | 1641 | 289.54 | 240.95 | 222 | 111 | 119 | 222 | 386 |
| **Land Use** | | | | | | | | | |
| Residential | 0 | 1 | 0.96 | 0.203 | 1 | 1 | 1 | 1 | 1 |
| Industrial | 0 | 1 | 0.04 | 0.203 | 0 | 0 | 0 | 0 | 0 |

[a] Season: Winter = 1, Summer = 2, Fall = 3.
[b] Shoulder Day: Monday/Friday = 1, Other = 0.
[c] Parking: No Parking = 0, One-Sided = 1, Two-Sided = 2.
[d] Passenger Vehicles = 1, Single Unit Trucks =2, Combination Trucks = 3, Multi-Trailer Trucks = 4

## 4. Methodology

Mixed-effects logistic regression was used in the data analysis. The choice of logistic regression was related to the fact that it makes no assumptions about the distributions of the independent variables, which in this case are presented as binary, continuous, and categorical variables. Moreover, the categorical nature of the response (compliance) also makes it difficult to meet the assumptions of the ordinary linear regression.

Furthermore, the advantage of using mixed effects logistic regression as opposed to standard logistic regression is that the former accounts for unobserved correlation between the elements of different groups or clusters by adding a random effects variable to the model. Since the 35 million data points considered in the analysis come from around 600 different locations, variation between different locations (groups) is expected. Although part of this variation could be accounted for using the location-based fixed effects considered in the model (e.g., land use and PSL), part of the variation remains unknown and can only be modelled by including this random effect parameter.

Data was modelled using a cumulative logit model with random intercepts. Let C (c= 1, 2, 3, … C) denote the number of ordinal response categories, which are represented in the proportional response model through the cumulative category comparisons C-1. The conditional cumulative probabilities of the outcome variable $Y_{ij}$ can then be expressed as follows:

$$P_{ijc} = \Pr(Y_{ij} \leq c \mid v_i, x_{ij}) = \sum_{c=1}^{C} P_{ijc}$$

The cumulative logits are then formulated as follows:

$$\log\left\{\frac{\Pr(Y \leq c)}{\Pr(Y > c)}\right\} = \eta_{ijc}$$

Where $\eta_{ijc}$ is the linear predictor, which is denoted as the following:

$$\eta_{\mathrm{ijc}} = \gamma_c - \lfloor \mathbf{x}'_{\mathbf{ij}}\boldsymbol{\beta} + \mathbf{z}'_{ij}\mathbf{v}_{\mathbf{i}} \rfloor$$

Where, $\boldsymbol{x'_{ij}}$ is a vector of the predictor variables; $\beta$ is the column vector of the fixed-effects regression coefficients; $\boldsymbol{z'_{ij}}$ is the design matrix for the random effects (the random equivalent of $\boldsymbol{x'_{ij}}$); C-1 is increasing such that $\gamma_c = \gamma_1 < \gamma_2 ..... < \gamma_{C-1}$; and the linear predictor depends on the response category only through the intercepts (cutoffs) $\gamma_c$. Since the ordinal model is defined based on cumulative probabilities it is represented through the difference of two conditional cumulative probabilities. Let $\psi(\eta_{ij,c})$ denote the logistic cumulative distribution function (cdf); the odds ratio of comparing two conditions is then represented by linear predictors as follows:

$$\psi(\eta_{ij,c}) - \psi(\eta_{ij,c-1})$$

All models were fitted using the PROC GLIMMIX procedure in SAS version 9.4 (SAS Institute, 2013).

## 5. Results

Before presenting the effects of each fixed variable on compliance, it is important to note that, although the odds ratio enables better understanding of the effects, in mixed models regression the interpretation of results using the odds ratio should be done with care. The odds ratio measures the effects of a unit change in a certain variable on the likelihood of the response, while assuming that all other variables remain fixed. The reason this is not practical in mixed models regression is because this assumption includes the random effects as well, which are often difficult to control.

With respect to roadside features on arterial roads (see Table 4), an increase in the number of lanes and parking (no parking, one-sided, or double-sided) both increase the likelihood of driver compliance to speed limits. Increases in those features increase compliance by 1.39 and 2.51 times for the number of lanes and parking respectively. In contrast, these features are negatively correlated with compliance on collector roads (see Table 5) (i.e., the degree of non-compliance is higher on collector roads with a greater number of lanes and more on-street parking).

The presence of vertical alignments, medians, and shoulders (the latter two are statistically insignificant on collectors) all reduced the probability of drivers abiding by speed limits on both arterials and collectors. Regarding land use categories, the following results were observed. In the case of collector roads, the odds of compliance dropped in industrial areas when compared to residential districts. As for arterials, the odds of compliance dropped in both commercial and agricultural areas when compared to direct control areas.

Locations with higher PSL experienced higher compliance on both arterial and collector roads. Moreover, drivers were also more likely to follow the speed limits during peak hours on arterials; however, the opposite is observed on collector roads, where the odds of compliance drop to 0.914 during peak hours.

When considering climate conditions, the variables considered had significant, yet marginal, effects on compliance. This was true for both arterials and collector roads, as evident from the results in tables 4 and 5. Marginal effects were also observed for shoulder days, with arterials experiencing a slight drop in compliance odds on those days (0.3%) and collectors experiencing a slight increase (2%).

The covariance parameter estimate ($\hat{\sigma}_c^2$), which represents the magnitude of the random variation between sites on a logit scale was equal to 1.41 (S.E= 0.1381) for arterial roads. The estimate was lower for the model including collector roads only, and it was equal to 0.8784 (S.E = 0.0823). These estimates indicate higher random variation between and within sites, indicating the importance of using mixed models regression in the analysis.

In order to assess model fit, the model was run with compliance as a binary variable, where compliance is represented as "1." The ratio of the Generalized Chi Squared ($\chi^2$) to the degrees of freedom (df), which measures the variability of the residuals in the marginal distribution of the data, was equal to 1.0 in both the arterial and the collector models. In general, it is seen that a small $\chi^2$ value relative to the df of the model indicate a good fit, which is the case in our models. According to Byrne (1989), a $\chi^2$/df ratio of less than 2.0 indicates a reasonable fit; similarly, Kline (1998) found that a ratio of 3.0 or less is a reasonably good indicator of the model's fit.

Finally, it is worth noting that in the case of arterials, the only variables that were found to be statistically insignificant at the 5% level are the presence of bus stops, pedestrian crossing and horizontal curves (HA). In the case of collector roads, the results show that the visibility and the presence of medians, horizontal curves and pedestrian crossings are all highly insignificant, statistically. Moreover, bus stops, bike lanes and shoulders are slightly insignificant, recording *p*-values of 0.08, 0.1616 and 0.1187 respectively. It is also worth mentioning that interactions between variables were tested; however, the effects were marginal, and hence, they are not included in the final models.

**Table 4: GLMM Model for Arterial Roads**

| Effect | Estimate | SE[*] | t Value | Pr > $\lvert t \rvert$[**] | OR[***] | 95% CI Lower | 95% CI Upper |
|---|---|---|---|---|---|---|---|
| Intercept 1 | -7.522 | 0.343 | -21.95 | <.0001 | NA | | |
| Intercept 2 | -6.562 | 0.343 | -19.15 | <.0001 | NA | | |
| Intercept 3 | -5.622 | 0.343 | -16.41 | <.0001 | NA | | |
| Intercept 4 | -3.923 | 0.343 | -11.45 | <.0001 | NA | | |
| **Road Features** | | | | | | | |
| Median | -0.660 | 0.206 | -3.2 | 0.001 | 0.517 | 0.345 | 0.774 |
| PSL | 0.150 | 0.000 | 719.07 | <.0001 | 1.161 | 1.161 | 1.162 |
| Lanes | 0.333 | 0.158 | 2.11 | 0.035 | 1.395 | 1.024 | 1.899 |
| Horizontal Alignment | -0.189 | 0.180 | -1.05 | 0.293 | 0.828 | 0.582 | 1.177 |
| Shoulder | -1.185 | 0.273 | -4.34 | <.0001 | 0.306 | 0.179 | 0.522 |
| Parking | 0.923 | 0.164 | 5.61 | <.0001 | 2.516 | 1.823 | 3.473 |
| Vertical Alignment | -0.883 | 0.427 | -2.07 | 0.039 | 0.414 | 0.179 | 0.956 |
| Bus Stop | 0.141 | 0.172 | 0.82 | 0.412 | 1.151 | 0.823 | 1.611 |
| Pedestrian Crossing | -0.027 | 0.353 | -0.08 | 0.939 | 0.973 | 0.487 | 1.945 |
| **Land Use** | | | | | | | |
| Agricultural | -2.705 | 0.459 | -5.89 | <.0001 | 0.067 | 0.027 | 0.164 |
| Urban service | -0.195 | 0.544 | -0.36 | 0.721 | 0.823 | 0.284 | 2.390 |
| Commercial | -0.494 | 0.196 | -2.52 | 0.012 | 0.610 | 0.416 | 0.896 |
| Direct Control | 0.000 | . | . | . | 1.000 | | |
| **Vehicle Class** | | | | | | | |
| Veh Class 1 | -0.849 | 0.006 | -137.94 | <.0001 | 0.428 | 0.423 | 0.433 |
| Veh Class 2 | -1.594 | 0.006 | -263.26 | <.0001 | 0.203 | 0.201 | 0.205 |
| Veh Class 3 | -0.430 | 0.007 | -64.63 | <.0001 | 0.651 | 0.642 | 0.659 |
| Veh Class 4 | 0.000 | . | . | . | 1.000 | | |
| **Climate Factors** | | | | | | | |
| Temperature | 0.003 | 0.000 | 51.7 | <.0001 | 1.003 | 1.003 | 1.003 |
| Wind Speed | 0.001 | 0.000 | 19.79 | <.0001 | 1.001 | 1.001 | 1.001 |
| Visibility | -0.002 | 0.000 | -19.26 | <.0001 | 0.998 | 0.998 | 0.999 |
| Season 1 | -0.243 | 0.010 | -23.26 | <.0001 | 0.785 | 0.769 | 0.801 |
| Season 2 | -0.219 | 0.001 | -170.78 | <.0001 | 0.804 | 0.802 | 0.806 |
| Season 3 | 0.000 | . | . | . | 1.000 | | |
| **Temporal Factors** | | | | | | | |
| Shoulder Day | -0.003 | 0.001 | -4.41 | <.0001 | 0.997 | 0.995 | 0.998 |
| Peak/OffPeak | 0.085 | 0.001 | 86.57 | <.0001 | 1.089 | 1.086 | 1.091 |
| **Volume Measure** | | | | | | | |
| Volume | 0.000 | 0.000 | Infty | <.0001 | 1.000 | 1.000 | 1.001 |

*SE: Standard Error
**Pr > |t|: Significance *p*-value
***OR: Odds Ratio
NA: Not Applicable, CI: Confidence Interval of the Odds Ratio
NOTE: p-value<0.05 indicates significance.

**Table 5: GLMM Model for Collector Roads**

| Effect | Estimate | SE* | t Value | Pr > \|t\|** | OR*** | 95% CI Lower | 95% CI Upper |
|---|---|---|---|---|---|---|---|
| Intercept 1 | -6.476 | 0.500 | -12.96 | <.0001 | NA | | |
| Intercept 2 | -5.545 | 0.500 | -11.1 | <.0001 | NA | | |
| Intercept 3 | -4.651 | 0.500 | -9.31 | <.0001 | NA | | |
| Intercept 4 | -3.169 | 0.500 | -6.35 | <.0001 | NA | | |
| **Road Features** | | | | | | | |
| Median | -0.001 | 0.318 | 0 | 0.997 | 0.999 | 0.536 | 1.861 |
| PSL | 0.163 | 0.004 | 41.4 | <.0001 | 1.177 | 1.168 | 1.186 |
| Lanes | -1.480 | 0.317 | -4.67 | <.0001 | 0.228 | 0.122 | 0.424 |
| Horizontal Alignment | 0.059 | 0.126 | 0.47 | 0.637 | 1.061 | 0.830 | 1.357 |
| Shoulder | -0.818 | 0.524 | -1.56 | 0.119 | 0.441 | 0.158 | 1.233 |
| Parking | -0.228 | 0.115 | -1.99 | 0.047 | 0.796 | 0.635 | 0.997 |
| Vertical Alignment | -2.874 | 0.945 | -3.04 | 0.002 | 0.056 | 0.009 | 0.360 |
| Bike Lane | -0.347 | 0.248 | -1.4 | 0.162 | 0.707 | 0.435 | 1.149 |
| Bus Stop | -0.221 | 0.127 | -1.75 | 0.081 | 0.802 | 0.626 | 1.028 |
| Pedestrian Crossing | -0.092 | 0.189 | -0.49 | 0.624 | 0.912 | 0.630 | 1.319 |
| **Land Use** | | | | | | | |
| Industrial | -0.894 | 0.404 | -2.21 | 0.027 | 0.409 | 0.185 | 0.903 |
| Residential | 0.000 | . | . | . | 1.000 | | |
| **Vehicle Class** | | | | | | | |
| Veh Class 1 | 1.535 | 0.024 | 63.69 | <.0001 | 4.640 | 4.426 | 4.864 |
| Veh Class 2 | 0.669 | 0.024 | 27.94 | <.0001 | 1.952 | 1.862 | 2.046 |
| Veh Class 3 | 1.402 | 0.025 | 56.85 | <.0001 | 4.062 | 3.870 | 4.263 |
| Veh Class 4 | 0.000 | . | . | . | 1.000 | | |
| **Climate Factors** | | | | | | | |
| Temperature | 0.001 | 0.000 | 6.13 | <.0001 | 1.001 | 1.001 | 1.002 |
| Wind Speed | -0.001 | 0.000 | -5.32 | <.0001 | 0.999 | 0.999 | 1.000 |
| Visibility | 0.000 | 0.000 | -1.29 | 0.198 | 1.000 | 0.999 | 1.000 |
| Season 1 | -0.313 | 0.012 | -26.46 | <.0001 | 0.731 | 0.714 | 0.748 |
| Season 2 | -0.137 | 0.007 | -19.86 | <.0001 | 0.872 | 0.861 | 0.884 |
| Season 3 | 0.000 | . | . | . | 1.000 | | |
| **Temporal Factors** | | | | | | | |
| Shoulder Day | 0.010 | 0.002 | 4.68 | <.0001 | 1.010 | 1.006 | 1.014 |
| Peak/OffPeak | -0.090 | 0.003 | -35.17 | <.0001 | 0.914 | 0.909 | 0.918 |
| **Volume Measure** | | | | | | | |
| Volume | 0.001 | 0.000 | 89.03 | <.0001 | 1.001 | 1.001 | 1.001 |

*SE: Standard Error
**Pr > |t|: Significance p-value
***OR: Odds Ratio
NA: Not Applicable, CI: Confidence Interval of the Odds Ratio
NOTE: p-value<0.05 indicates significance.

# 6. Discussion and Practical Implications

## *6.1 Discussion*

As noted earlier, an increase in on-street parking seems to be positively correlated with compliance on arterial roads, an observation that is in line with outcomes of previous research (Marshall *et al.*, 2008). This could be attributed to greater caution by drivers when observing parked cars on one or both sides of the road. Similarly, increasing the number of lanes on a road, but keeping all else equal, also encourages drivers to comply with speed limits on arterials. With traffic volume controlled for in the model, this could be a matter of drivers sensing the presence of adjacent vehicles and thus being more cautious, or even using the surrounding vehicles to judge an acceptable operating speed—something which has been found to influence compliance in the past (Houten and Nau, 1983, Haglund and Åberg, 2000). Another explanation could be that a larger number of lanes might result in narrower lane width, a factor which has some association with lower speed choice (Fitzpatrick *et al.*, 2001).

Alternatively, the presence of a shoulder seems to reduce the odds of drivers obeying speed limits by 70% on arterials. The findings above seem to imply that the more lateral space drivers have, the less likely they are to abide by PSL; whereas, if the space available to the drivers decreases, they become more restrained and less likely to violate the PSL. It is worth noting here that previous studies also found a positive association between roads of increased shoulder width and higher speeds (for example, see (Giles, 2004)).

Regarding road geometry, as indicated in previous work (Fitzpatrick *et al.*, 2001), the presence of medians (significant on arterials only) and vertical alignments were both observed to increase the probability of speed limit violation. The presence of a median or physical separation, as expected, encourages speeding and, as a result, non-compliance, which is likely due to the subjective (implied) and objective (actual) safety it provides to drivers. In the case of vertical alignments, not much can be inferred unless data on the directional traffic volumes become available; however, it is important to note that they are associated with significant drops in compliance odds for both arterials and collectors.

Unlike arterials, on collector roads, the number of lanes and on-street parking seem to have negative effects on compliance. The presence of parking is associated with a drop of just over 20% in the likelihood of compliance. Moreover, the drop due to the increase in the number of lanes is over 75%. Another variable for which behaviour on collectors is opposite to that on arterials is the peak hours. The compliance odds during peak hours on collector roads experience a decrease of 9% when compared to off-peak hours.

Since a measure of exposure has been included in each of the models, it would not be appropriate to attribute the differences in some observations between arterials and collectors to the differences in traffic volumes. Moreover, the fact that congestion effects have also been eliminated from the model indicates that the differences are not due to traffic density on the different road classes.

As already indicated, peak hours when compared to off-peak hours encourage a higher likelihood of compliance on arterial roads only. Similarly, shoulder days (Monday and Friday), when compared to other days of the week, slightly increased the possibility of drivers obeying speed limits on collector roads. Since congestion effects have been omitted from the dataset, these results could be a matter of drivers being vigilant and driving at conservative speeds to account for the risks imposed by higher activity on the roads during those times. Similar conclusions can be inferred from the fact that at higher PSL, drivers are more likely to comply with speed limits, with the odds rising around 16% and 17% on arterials and collectors respectively. This is a positive finding, which also implies that drivers realize the increased risks of violation at higher speeds. Increases in volume are also expected to increase the likelihood of drivers complying with the PSL on both arterial and collector roads.

When taking into account climate factors, summer months experience lower compliance rates than fall. As for the other climate factors considered (temperature, wind speed and visibility), their effects remain difficult to interpret since they have odds ratios almost equal to one in both the arterial and collector models. This implies balanced probabilities in terms of effects on compliance; however, all variables, apart from visibility on collector roads, remain statistically significant. One thing to note though is that increases in visibility on arterials result in a slight reduction in the odds of a driver complying with the PSL. Although visibility here is weather related, it comes in line with findings from Goldenbeld and van Schagen (2007), who concluded that a driver's perceived safe speed limit is higher on roads where vegetation or trees are absent (i.e., more visibility).

Examining the effects of land use on compliance, it is found that for collector roads, industrial areas recorded higher odds of violation when compared to residential areas with the probability of compliance dropping by almost 60%. On arterial roads, locations of direct control land use recorded the highest compliance rates with a relative drop in probability in both commercial and agricultural areas by 39% and 94% respectively. It is worth noting here that Galin (1981) also observed higher speed choices in agricultural areas compared to residential. A possible explanation for this is that drivers typically feel that open areas (less built-up) warrant higher speed limits due to the increased field of vision and sight distance; consequently, drivers may restrain from complying with the PSL. It is worth noting here that previous research found that the absence of buildings alongside the road, better than average sight distance and clarity of situation were associated with an increase in the speed that drivers perceive to be safe (Goldenbeld and van Schagen, 2007). Lower compliance in industrial areas on collector roads could also be a matter of lower pedestrian activity in those areas.

A further finding by the model was that the effects of vehicle classes on the likelihood of compliance with speed limits fluctuates between different vehicle classes. Nonetheless, a general observation is that single-unit trucks (including pickup vans) seem to record higher odds of violation than passenger vehicles and combination trucks. These results seem consistent with previous findings (Giles, 2004).

### *6.2 Practical Implications*

The effects observed in this study statistically validate the existence of a relationship between features of the road environment and driver compliance to speed limits. This indicates that driver compliance with speed limits can be influenced through modifications of those features, verifying the concept of speed limit credibility. For instance, according to the outcomes of this study, drivers are more likely to accept current speed limits on an arterial road that is not physically divided, has more lanes (with potentially narrower lane width), has one- or two-sided parking and no shoulder compared to an arterial with less lanes, no parking, and a shoulder. This shows that the combined effect of all the different road features and the road environment must be considered when legislators are considering selecting a speed limit on a certain road. The results of this study and others can also be used to understand whether current speed limits posted on roads in the city of Edmonton and, potentially other cities, are in line with driver expectations; if not, slight modifications to the roadway environment, such as removing the shoulder on the road, might help achieve higher compliance rates. This could be an alternative method for dealing with high speed violations, particularly at locations where more enforcement activity is not effective.

It is worth noting here that proposals for potential modifications to the road environment should only be done once the impacts of such a change on other aspects of safety have been studied. In other words, although removing a shoulder might result in higher compliance rates, understanding the effects of such a change on other aspects of traffic safety is essential before such a change is adopted. Therefore, holistic safety analysis is always required before any changes to the road environment are implemented.

It is clear from the analysis that not all the variables considered can be controlled by a designer. For instance, land use and temperature are obviously variables that cannot be changed. Despite that, the information inferred form the effects of those variables on compliance choice is useful when setting speed limits for new roads or when deciding on an enforcement strategy for a group of locations or during different times in the year. For instance, speed enforcement activity could be tailored to fit times when higher violation activity is expected due to weather condition or at locations of particular land use. The land use variable would also be important when setting a speed limit at a new location; similarly, if the vehicles expected to be using the road are predominantly single-unit trucks, this might also be taken into consideration.

## 7. Conclusions and Future Research

As already stated, establishing credible speed limits is an extremely important matter, which could have significant impacts on driver compliance. However, establishing those credible limits is only possible if the factors that influence driver compliance are identified. Identifying those factors would eventually enable designers and enforcement officials to use this information in future efforts of setting and enforcing such limits.

This study used data collected on urban roads in the city of Edmonton to identify factors that influence driver compliance with speed limits. The speed data consisted of more than 35 million different observations and came from 600 different arterial and collector roads in the city. The current study contributes to the existing literature on speed limit credibility in that: (i) It analyzes empirical data from the field as opposed to questionnaire data. (ii) The analysis is performed on actual driver compliance, not on perceived safe speed, speed choice or preferred speed. (iii) The study considers the effects of a variety of different factors on compliance, including the effects of dynamic factors such as temporal and weather factors.

In general, the following conclusions can be drawn from the modelling results. The results indicate that the more physically constrained drivers become and the less safe they feel, the more likely they are to obey speed limits. The study also shows that drivers are vigilant of the risks of exceeding PSLs during higher activity periods and at higher speeds. In addition, the paper also highlighted some variables that have contrasting effects on driver compliance when comparing arterial and collector roads; this is of extreme importance to road designers since it shows that a feature, which could promote speed limit credibility on an arterial road, might have different effects on collectors. This is something that could be further investigated by developing different models for roads of different land use, road category (rural/urban), or even different speed limits. Although this study developed different models for segments of different road class (arterials and collectors), further refinement of the analysis is still possible, such as developing different models for different seasons.

Moreover, it is recommended that future studies also consider the effects of design attributes of the geometric features on compliance. Due to data limitations, the majority of the features considered in this paper were represented using binary variables. For instance, although the presence/absence of horizontal curves was found to have no statically significant effect on compliance, the microscopic attributes of those curves (e.g., degree of curvature, radius of curve) could reveal different outcomes. Analyzing the effects of microscopic road attributes on driver compliance could provide further insight for experts when designing new roads or deciding on credible speed limits for already designed roads. The effects of latent variables such as driver attitude could have significant impact on the choice of compliance and, therefore, must be considered in future work.

Another limitation of the study is the inability to include enforcement activity as part of the models due to data limitations. Similarly, the directional split of traffic on vertical alignments was also unknown. This factor might affect the way the outcomes could be interpreted; therefore, it is important that future research takes this into account. Information about on-street parking occupancy could also provide more inference about the effects of that variable. With that being said, the outcomes with regards to the statistical significance of those variables are still of great value.

In summary, the analysis performed in this research further validates the concept of speed limit credibility and the role the road environment plays in a driver's perception of an acceptable speed limit. Although it is still not possible, based on the outcomes of a single study, to establish guidelines for setting credible speed limits, the current research shows that establishing such a guideline is possible if the outcomes of this study are validated using more empirical data addressing the aforementioned gaps in the literature.

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**References**

Aarts, L., Van Nes, N., Wegman, F., Van Schagen, I., Louwerse, R., Year. Safe speeds and credible speed limits (sacredspeed): New vision for decision making on speed management. In: Proceedings of the Transportation Research Board 88th Annual Meeting.
Aarts, L., Van Schagen, I., 2006. Driving speed and the risk of road crashes: A review. Accident Analysis & Prevention 38 (2), 215-224.
Aljanahi, A., Rhodes, A., Metcalfe, A.V., 1999. Speed, speed limits and road traffic accidents under free flow conditions. Accident Analysis & Prevention 31 (1), 161-168.
Byrne, B.M., 1989. A primer of lisrel: Basic applications and programming for confirmatory factor analytic models Springer-Verlag Publishing.
City of Edmonton, 2012. Design and construction standards. Volume 2.
Coe, 2015. Population forecasts.
Consortium, S., 2004. European drivers and road risk. Institut National de Recherché sur les Transports et Securite June.
Coral Sales Company, 2016. M.H. Corbin nc-300 in-roadway traffic analyzer.
Duncan, N., 1974. Rural speed/flow relations.
Elvik, R., Amundsen, A.H., 2000. Improving road safety in sweden. TØI report 490, 2000.
Fhwa, 2001. Guide, traffic monitoring. US Department of Transportation, Washington, DC.
Figueroa Medina, A., Tarko, A., 2005. Speed factors on two-lane rural highways in free-flow conditions. Transportation Research Record: Journal of the Transportation Research Board (1912), 39-46.
Fildes, B., Rumbold, G., Leening, A., 1991. Speed behaviour and drivers' attitude to speeding. Monash University Accident Research Centre, Report 16.
Finch, D., Kompfner, P., Lockwood, C., Maycock, G., 1994. Speed, speed limits and accidents. TRL project report (PR 58).
Fitzpatrick, K., Carlson, P., Brewer, M., Wooldridge, M., 2001. Design factors that affect driver speed on suburban streets. Transportation Research Record: Journal of the Transportation Research Board 1751 (1), 18-25.
Fitzpatrick, K., Miaou, S.-P., Brewer, M., Carlson, P., Wooldridge, M.D., 2005. Exploration of the relationships between operating speed and roadway features on tangent sections. Journal of Transportation Engineering 131 (4), 261-269.
Galin, D., 1981. Speeds on two-lane rural roads-a multiple regression analysis. Traffic Engineering & Control 22 (HS-032 645).
Gargoum, S., El-Basyouny, K., Year. Analyzing driver compliance to speed limits using logistic regression. In: Proceedings of the Transportation Research Board 94th Annual Meeting.

Giles, M.J., 2003. Correcting for selectivity bias in the estimation of road crash costs. Applied Economics 35 (11), 1291-1301.
Giles, M.J., 2004. Driver speed compliance in western australia: A multivariate analysis. Transport Policy 11 (3), 227-235.
Goldenbeld, C., Van Schagen, I., 2007. The credibility of speed limits on 80km/h rural roads: The effects of road and person (ality) characteristics. Accident Analysis & Prevention 39 (6), 1121-1130.
Haglund, M., Åberg, L., 2000. Speed choice in relation to speed limit and influences from other drivers. Transportation Research Part F: Traffic Psychology and Behaviour 3 (1), 39-51.
Hauer, E., Ahlin, F., Bowser, J., 1982. Speed enforcement and speed choice. Accident Analysis & Prevention 14 (4), 267-278.
Houten, R., Nau, P.A., 1983. Feedback interventions and driving speed: A parametric and comparative analysis. Journal of Applied Behavior Analysis 16 (3), 253-281.
Islam, M.T., El-Basyouny, K., 2013. An integrated speed management plan to reduce vehicle speeds in residential areas: Implementation and evaluation of the silverberry action plan. Journal of safety research 45, 85-93.
Islam, M.T., El-Basyouny, K., Ibrahim, S.E., Year. The impact of lowered residential speed limits in the city of edmonton. In: Proceedings of the Transportation Research Board 92nd Annual Meeting.
Ivan, J.N., Garrick, N.W., Hanson, G., 2009. Designing roads that guide drivers to choose safer speeds.
Kanellaidis, G., Golias, J., Zarifopoulos, K., 1995. A survey of drivers' attitudes toward speed limit violations. Journal of safety Research 26 (1), 31-40.
Kline, R., 1998. Principles and practice of structural equation modeling (guilford, new york, ny).
Laapotti, S., Keskinen, E., Rajalin, S., 2003. Comparison of young male and female drivers' attitude and self-reported traffic behaviour in finland in 1978 and 2001. Journal of safety research 34 (5), 579-587.
Ltsa, 2003. Setting of speed limits 2003. In: Authority, L.-L.T.S. ed. Land Transport Rule, New Zealand. New Zealand.
Marshall, W., Garrick, N., Hansen, G., 2008. Reassessing on-street parking. Transportation Research Record: Journal of the Transportation Research Board (2046), 45-52.
Mclean, J., 1981. Driver speed behaviour and rural road alignment design. Traffic Engineering & Control 22 (HS-032 471).
Misaghi, P., Hassan, Y., 2005. Modeling operating speed and speed differential on two-lane rural roads. Journal of Transportation Engineering 131 (6), 408-418.
Nhtsa, 2012. Traffic safety facts, nhtsa, us department of transportation, 2009.
Nouvier, J., 1990. Vitesses pratiquées sur autoroutes de liaison. In: Lyon., C.D. ed.
O'flaherty, C., Coombe, R., 1971. Speeds on level rural roads: A multivariate approach. Traffic Engng Control 13 (1-3).
Oecd/Ecmt, 2006. Speed management. Paris: OECD, Joint Transport Research Committee, Paris.
Onisr, 2005. Bilan de l'année 2004. In: Routière, O.N.I.D.L.S. ed. Ministère des Transports, Paris.
Pasanen, E., Salmivaara, H., 1993. Driving speeds and pedestrian safety in the city of helsinki. Traffic Engineering and Control 34 (6), 308-310.
Quimby, A., Maycock, G., Palmer, C., Buttress, S., 1999. The factors that influence a driver's choice of speed: A questionnaire study Transport Research Laboratory.

Rienstra, S.A., Rietveld, P., 1996. Speed behaviour of car drivers: A statistical analysis of acceptance of changes in speed policies in the netherlands. Transportation Research Part D: Transport and Environment 1 (2), 97-110.

Road Safety Canada Consulting, 2011. Road safety in canada. March 2011 ed.

Sas Institute, 2013. 9.4 ed., Cary, NC, USA.

Van Schagen, I., Wegman, F., Roszbach, R., 2004. Safe and credible speed limits: A strategic exploration.

Várhelyi, A., 1997. Dynamic speed adaptation based on information technology-a theoretical background. Lund University.

Vogel, K., 2002. What characterizes a "free vehicle" in an urban area? Transportation Research Part F: Traffic Psychology and Behaviour 5 (1), 15-29.

Walton, D., Bathurst, J., 1998. An exploration of the perceptions of the average driver's speed compared to perceived driver safety and driving skill. Accident Analysis & Prevention 30 (6), 821-830.

Wasielewski, P., 1984. Speed as a measure of driver risk: Observed speeds versus driver and vehicle characteristics. Accident Analysis & Prevention 16 (2), 89-103.

Wilmot, C.G., Khanal, M., 1999. Effect of speed limits on speed and safety: A review. Transport Reviews 19 (4), 315-329.

Yagar, S., Van Aerde, M., 1983. Geometric and environmental effects on speeds of 2-lane highways. Transportation Research Part A: General 17 (4), 315-325.