Vehicle Operating Speed on Urban Arterial Roadways

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16. Abstract

This research explored (1) the relationship between suburban vehicle operating speed and roadway characteristics, especially the presence of bicyclists and (2) if crowdsourced speed data could be used to estimate the unconstrained speed for a location. Both vehicle volume per lane and bicycle volume were found to be influential in affecting average speed on lower speed urban arterial roadways. For 40.3 km/hr [25 mph] sites, an increase of 19 vehicles per 15-min period will decrease average speed by 1.6 km/hr [1 mph], and an increase of more than 39 bicyclists per 15-min period will decrease average vehicle speed by a similar amount. Because of the limited number of 15-min periods with bicycle counts greater than 1, the research team also developed a model using all available 15-min periods with on-road speed data. Speed and volume data in 15-minute increments for two weeks at nine sites were obtained using on-road tubes and from a vendor who sells crowdsourced speed data. The difference between the tube data and the crowdsourced data was calculated and called TMCS. The geometric variables that had the greatest influence on TMCS were the number of signals and the number of driveways within a corridor. When only including non-congested periods, weekends (Saturday or Sunday) were associated with the smallest TMCS.

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Introduction

Due to the mounting evidence on health benefits and air pollution reduction, bicycling as a transportation mode has been becoming more popular in the recent years resulting in the addition of more on-street bicycle lanes and separated bicycle facilities [1, 2]. McKenzie reported that the number of U.S. bike commuters increased from about 488,000 in 2000 to about 786,000 in 2008–2012 representing the largest percentage increase among all travel modes [3]. Greater emphasis on bicyclist safety is required as the bicyclists are more vulnerable than vehicle drivers are. The concept of 'safety in numbers' hypothesis supports the idea that vehicle speeds may be affected. The hypothesis is that, as more people cycle, it becomes safer because more cyclists are more visible to motorists, which may, in turn, makes driver cautious about keeping sufficient lateral spaces and reducing speed [4]. Identifying the amount of the speed change because of the presence of bicyclists could help to understand better the potential for changes in bicyclist-vehicle crashes, including variations in severity level of the crashes. The primary goal of this research is to identify key contributing factors that influence vehicle operating speed in the presence of bicyclists on urban arterials.

With the collection of on-road speed data, the opportunity is present to compare the on-road speed data with crowdsourced data. Emerging technologies, such as Bluetooth or GPS probe vehicle, collect travel time (and speed) data. Private companies are collecting and selling the data for several applications. Due to the expense of collecting on-site travel performance measures such as delay or spot speeds, and with the growing availability of crowdsourced data, is there a reasonable protocol for using crowdsourced data as a representation of the operating speed at a select location or along a corridor?

Background

Speed on Arterial Streets

Based upon information in the literature [5], several arterial street segment characteristics are known or suspected to affect a driver's speed choice. In general, the following relationships were found:

- Operating speeds decrease as the access density increases.
- Operating speeds decrease as the roadside becomes fuller with objects.
- Operating speeds are higher with higher posted speed limits.
- Operating speeds are lower on horizontal curves with small radii or larger deflection angle.

The research team will obtained these roadway segment characteristics along with others for the evaluation.

Bicycle Presence

A limited number of studies exists on vehicle operations in the presence of bicyclists. Majority of the studies focused on either the safe lateral distance or the comfort levels of the bicyclists. Li et al. reported that vehicle flow is an important factor affecting bicycle travelers' perception of comfort on on-street bike lanes [6]. Chen et al. reported reducing speeding nature of motorists to establish that installation of bicycle lanes did not lead to an increase in crashes [7]. Parkin and Meyers collected quantitative data regarding the passing distances between vehicles and bicyclists [8]. This study suggested that where cycle lanes are present drivers may be driving within the confines of their own marked lane with less recognition being afforded to the cyclist. Love et al. developed a linear regression model relating Vehicle Passing Distances (VPD) to quantitative variables like lane width, bicycle infrastructure, cyclist and street identity [9]. Using data from six cities in Ottawa with shared routes and with and without bike lanes, Apasnore et al. formulated a linear regression model [10]. The study found that motor vehicle speed and volume, lane width, number of through lanes, bicycle speed, bicycle position from adjacent curb edge line, adjacent curb parking, and grade slope are significant factors that impact lateral spacing between bicycles and vehicles. The current literature search suggests no qualification on the vehicle operating speed in presence of the bicyclists. The current research aims to mitigate the current research gap by developing a suitable dataset that can best address the research question. To quantify the association between average vehicle speed and other associated factors, the research team developed linear mixed effect models.

Performance Measures

Measuring a roadway's performance provides the opportunity to check the quality of a facility's operations. It enables a comparison of the current or anticipated operations to the standards or goals set for that facility. The checks can be performed on a routine basis in order to appraise whether the facility is still performing as desired or the checks could be part of the facility's design process. Performance measures identified to evaluate the quality of a road include traffic flow, travel time, congestion, travel time reliability, delay, and speed.

When identifying a posted speed limit for a facility, the *Manual on Uniform Traffic Control Devices* (MUTCD) [11] states, "When a speed limit within a speed zone is posted, it should be within 5 mph of the 85th-percentile speed of free-flowing traffic." Free-flow speeds represent the speed a driver selects when there are no interactions with other vehicles. For a roadway segment, several factors could influence free-flow speed such as roadside development or road conditions. Desirably, the free-flow speed should be close to the posted speed limit to decrease speed variability and improve the performance of the street.

The MUTCD also notes that "speed studies for signalized intersection approaches should be taken outside the influence area of the traffic control signal, which is generally considered to be approximately ½ mile, to avoid obtaining skewed results for the 85th-percentile speed." Because of the challenges with identifying free-flow vehicles within an urban environment, especially when signal spacing is less than a signal per mile, other speed measures could be considered as a performance measure.

National Cooperative Highway Research Program (NCHRP) Report 618 [12] and Moving Ahead for Progress in the 21st Century Act (MAP-21) [13] have encouraged performance based and result oriented program to attain national transportation goals by improving the efficiency of the surface transportation system. The MAP-21 program evolved into Congestion Mitigation and Air Quality Improvement Program (CMAQ) for developing performance requirements to improve air quality, mobility, traffic management, and mitigate congestion by performance evaluations [14].

Common speed-based performance measures include free-flow speed, desired speed, 85th percentile speed, average speed, unconstrained speed, and reference speed. In some cases, these speeds are measured in the field while in others the speed is predicted. The estimates of some predicted speeds use base free-flow speed. The Transportation Research Board Highway first published the Highway Capacity Manual (HCM) in 1950. Major changes were introduced in HCM 2010 [15] related to level-of-service (LOS) calculation for arterials. Base free-flow speed for arterial street segments considers the effects of speed limit, access density, median type, curb presence, and signals.

Free-flow speed can be explained in many different ways depending on context and adaptability. For example, the HCM says free-flow speed is "the average speed of vehicles on a given segment, measured under low-volume conditions, when drivers are free to drive at their desired speed and are not constrained by the presence of other vehicles or downstream traffic control devices (i.e., traffic signals, roundabouts, or STOP signs" (*15*, page 4-5). A 2015 study in Delhi found the following factors as having a significant influence on free-flow speed for urban arterials: total vehicles; number of friction points (e.g., bus stops, pedestrian crossings), access points, intersections, flyovers; and length of the section under consideration [16].

In general, free-flow speed on arterials occurs under low volume conditions when the driver selects a speed unaffected by the presence of other vehicles on the segment with all greens in the trip. Theoretically, free-flow speed is defined as the speed which exists at zero density and flow rate on a given study segment [17], which is hard to obtain in practical conditions. Sekhar et al. considered flow rates between 0 to 1000 passenger cars per hour per lane with vehicles having a lead headway of 8 seconds and lag headway of 5 seconds to be included in the free-flow speed estimation [18]. A method to determine a curve advisory speed suggested that free-flow vehicles are like those with at least 3 seconds of space between leading and following vehicles [19].

The desired speed is defined as the speed, under free-flow conditions, that drivers choose to travel when not constrained by roadway design features [20].

Unconstrained speed can be defined as the comfortable speed that a driver would prefer on a given road segment when there is no vehicle interaction. Measuring unconstrained speed for an arterial is difficult due to the presence of signals and multiple driveways. Signal timing typically varies throughout the day to balance the demand on the different approaches and the demand during different times of the day. Locations with intense peaks, such as schools or offices, can affect travel patterns and operations.

The *Guide to Benchmarking Operations Performance Measures* discusses definitions for unconstrained travel time as follows:

> "Unconstrained Travel Time represents a reasonable estimate of travel time in the absence of congestion during good weather conditions. Two different methods of determining unconstrained travel time may optionally be used as the basis for the appropriate performance measures. The first method is preferred: 1. 85th percentile travel time (corresponding to the 85th percentile speed converted to an equivalent travel time) of traffic during off-peak periods. 2. Target travel time defined as the time it takes motorists to traverse a roadway section when they are traveling at speeds established by operations personnel as the desired speed for a given roadway under prevailing roadway and traffic conditions. Off-peak periods are defined as any time that traffic flow exhibits Level of Service C or better." [21, page 8]

The 2015 Urban Mobility Report [22] used overnight speeds to approximate the free-flow speeds that were used as a comparison standard. Such an approach may work well for freeway systems but perhaps not for arterials. Other organizations have developed unique approaches to determine reference speeds. For instance, FDOT considers free-flow speed as average speed where drivers are not controlled by traffic or roadway conditions and is assumed to be posted speed limit plus five [23].

Lomax et al. [24] renamed free-flow speeds for arterials as uncongested speeds and defined it as the average speed adopted by a driver on a road segment with no vehicle interaction along with given uniform roadway and traffic conditions. Overnight speeds from 10 pm to 5 am were used to identify the free-flow speeds to be used as the comparison standard in evaluating congestion.

Minnesota DOT [25] uses two reference speeds to evaluate the performance of arterials. One is light traffic speed as the average of the highest two speeds during 14 daytime hours (6 am to 8 pm) while the other is target speed, which is the light traffic speed adjusted by a signal density factor. Zhang and Chen [26] noted that reference speed does not work well for urban arterials with interrupted flows. They examined GPS-based speed data for statewide urban arterials in Kentucky and concluded that it is beneficial to use the daytime data, specifically, the 85th percentile speed as the reference speed.

Research Objectives

The objectives of this research were to explore (1) the relationships between suburban vehicle operating speed and the presence of bicyclists and (2) if crowdsourced speed data could be used to estimate the unconstrained speed for a location. These relationships may be based on the geometric and traffic control devices characteristics for the area; therefore, those variables were also obtained and used in the evaluations.

Data

The data collection had four main components: downloading the bicycle counts, recording the geometric and traffic control device attributes of the selected sites, collecting the speed-volume data using on-road pneumatic tubes, and obtaining crowdsourced data for a similar time. The research team fused these components during the data reduction efforts.

Site Selection

On-road tube speed data, crowdsourced data, and roadway characteristics were collected for several locations in the city of San Diego on urban street segments. The locations were selected based upon the availability of bike counter data.

San Diego Bicycle Data

The San Diego Regional Bike and Pedestrian Counter Network is one of the largest pedestrian and bicycle counting programs in the U.S. It is a collaborative effort between SANDAG, San Diego State University (SDSU), and the County of San Diego Health and Human Services Agency. The network was initially funded by a grant from the Centers for Disease Control and Prevention. Across 15 jurisdictions in the San Diego region, 59 counters have been installed.

The research team reviewed the locations in San Diego to identify the counters on roadway segments with on-road bicycle lanes. After reviewing the historical data for the on-road counter stations and the battery status of the counters, the research team selected eight roads. The battery status indicated whether the counter could still be actively collecting data when the vehicle operating speed and volume data would be collected. The chosen sites had bicycle counter operating 24 hours a day, seven days a week for on-road locations.

Pneumatic Road Tube Data

On-road tube data collection is a common method for collecting short-term vehicular speed and volume data. A local vendor installed the road tubes at the selected sites and recorded speed and vehicle volume data for most of the sites for the same two-week period. Due to technical issues, the vendor collected the speed/volume data for two of the sites after the initial group of sites. Within a 15-min period, vehicle volume is provided and the speed data are binned into five mph increasing groups. Table 1 lists the data collection periods by site number. Note that Site 6 and Site 8 represent the same road with different time periods for the bicycle and vehicle data.

Table 1. On-Site Data Collection

Site Number	Number of Sites	When	Duration
Site 1 to Site 5 (both directions) Site 8 (only eastbound)	11	08/08/2017-08/21/2017	Two weeks (total 14,784 15-minute bins)
Site 6 (both directions)	2	09/12/2017-09/18/2017	One week (total 1,344 15-minute bins)
Site 7 (both directions)	2	11/21/2017-12/04/2017	Two weeks (total 2,688 15-minutes bins)

Crowdsourced Data

Several vendors obtain crowdsourced data for a wide network of roads throughout the United States. These roads are split into segments with unique identification numbers. The research team identified the segment that included the site with the on-road tube data and purchased a month of data for the segments. The vendor provided the speed data as a collection of historic speed, travel time data, corridor speed, and the confidence value for each 15-minute period. For instance, speed entry at 11:00am would result in vehicle time and travel speed from 11:00am to 11:15 am on the given day. Each segment is directional, and the segment length may vary in a given direction at a site.

Geometric and Traffic Control Device Data

Several factors could influence operating speed such as geometric characteristics, traffic control devices, parking activity, and so on. The research team collected geometric variables using aerial photographs and used the street view function to obtain the posted speed limit. Table 2 summarizes the geometric and traffic control device variables that were influential in the analyses. Two roads (four sites) have 40.3 km/hr [25 mph] posted speed limit, and the rest of the sites have 72.5 km/hr [45 mph] posted speed limit. The number of through lanes ranges from 2 to 6. The number of signalized intersections within 1.6 km [1 mile] of the counter location range from 0 to 3 signals. Driveway densities are high in three sites (Site 2, Site 6, and Site 8). Out of eight sites, five of them have bus stops. The influence distance represents the distance between the on-road tube counter location and a feature that could influence speed at the counter, typically a signalized intersection. Most of the sites had a raised median with only Site 6 and 8 having a two-way left-turn lane. The typical average lane width was 3.4 m [11 ft] with one road having 4.0 m [13 ft] average lane widths. All sites have curb and gutter, level vertical alignment, two-way traffic, and sidewalks on both sides of the street. Additionally, all the selected sites have a bike lane with a pavement marking stripe separating them on at least one side of the street.

To aid in interpreting the modeling results, several variables were adjusted so that the minimum value would be 0. A base condition allows the ability to see the effects of an additional meter [foot] of lane width. Base conditions were also used for other variables, such as the number of signals or the number of driveways.

Table 2. Description of Key Variables

Site*	PSL km/h (mph)	CSL m (ft)	Ln	Sig	DWS	DWO	ID m (ft)	MW m (ft)	BS	PW m (ft)
SD01-NB	40.3 (25)	225 (739)	2	1	8	7	67.1 (220)	3.1 (10)	No	2.4 (8)
SD01-SB	40.3 (25)	225 (739)	2	1	8	7	39.7 (130)	3.1 (10)	No	4.3 (14)
SD02-NB	40.3 (25)	1031 (3379)	4	5	20	7	115.9 (380)	1.8 (6)	Yes	2.4 (8)
SD02-SB	40.3 (25)	789 (2587)	4	5	7	20	115.9 (380)	1.8 (6)	Yes	2.4 (8)
SD03-EB	72.5 (45)	644 (2112)	4	4	1	1	129.6 (425)	4.6 (15)	Yes	0 (0)
SD03-WB	72.5 (45)	644 (2112)	4	4	1	1	103.7 (340)	4.6 (15)	Yes	0 (0)
SD04-EB	72.5 (45)	644 (2112)	6	5	2	3	91.5 (300)	1.8 (6)	No	0 (0)
SD04-WB	72.5 (45)	644 (2112)	6	5	3	2	115.9 (380)	1.8 (6)	No	0 (0)
SD05-EB	72.5 (45)	531 (1742)	6	5	2	3	119 (390)	1.8 (6)	No	0 (0)
SD05-WB	72.5 (45)	531 (1742)	6	5	3	2	91.5 (300)	1.8 (6)	No	0 (0)
SD06-EB	72.5 (45)	1498 (4910)	4	3	22	33	161.7 (530)	3.1 (10)	Yes	0 (0)
SD06-WB	72.5 (45)	1498 (4910)	4	3	33	22	192.2 (630)	3.1 (10)	Yes	0 (0)
SD07-NB	72.5 (45)	NI	4	3	8	4	244 (800)	6.1 (20)	Yes	0 (0)
SD07-SB	72.5 (45)	NI	4	3	4	8	244 (800)	6.1 (20)	Yes	3.1 (10)
SD08-EB	72.5 (45)	1498 (4910)	4	3	22	33	161.7 (530)	3.1 (10)	Yes	0 (0)

*where:
BS = Bus stop present (yes or no).
CSL = Segment length for crowdsourced data (NI=not included as crowdsource data not available for evaluation), m (ft).
DWO = Number of driveways/unsignalized intersections 0.8 km (0.5 mi) either side of counter along opposite direction of travel.
DWS = Number of driveways/unsignalized intersections 0.8 km (0.5 mi) either side of counter along in same direction of travel.
ID = Distance between counter location and feature that could be influencing the speed speed measured at the on-road tube counter such as signalized intersection or roundabout, m (ft).
Ln = Number of through lanes in both directions.
MT = Median type (R=raised, T=two-way left-turn lane).
MW = Typical or average median width for the segment, m (ft).
PSL = Posted speed limit, km/hr (mph).
PW = On-street parking width, m (ft).
Sig = Number of signalized intersections 0.8 km (0.5 mi) either side of counter, including any signals at the begin or end of the segment.
Site = name assigned to the site.

Additional Variables

Based on the literature review along with initial exploratory analyses, several potential factors were identified that could affect the use of crowdsourced data as an estimate of arterial operating speed. These factors are discussed below.

Level of Service

In an urban environment, especially with the presence of signals and the amount of traffic present, vehicles are not able to travel at free-flow speeds for most of the day. To explore whether crowdsourced speed data are closer to a spot speed during certain traffic conditions, the research team calculated the level of service value for each 15-min period using the tube data.

The research team used the HCM 2010 methodology to predicting the base free-flow speed. Base free-flow speed includes an assumed speed constant that is a function of the posted speed limit. It also includes adjustments for median type, cross section (curb or no curb), access density, and segment length. For segments with signalized intersections, the base free-flow speed was adjusted following the directions included in the 2010 HCM. The measured speed for a 15-minute period as a percentage of the base free-flow speed was compared to the LOS criteria included in the HCM 2010, and a LOS was assigned to each 15-minute period. For example, if the travel speed represented between 67 and 85 percent of the free-flow speed, then the 15-minute period was operating at LOS B.

Light Level

Previous studies have demonstrated that natural light conditions affect speed (27); therefore, the light level (day, night, dusk, and dawn) for each 15-minute period was identified. The research team collected sunrise and sunset times for each day represented in the dataset and defined dawn as 30 minutes before-and-after sunrise and dusk as 30 minutes before-and-after sunset. Depending on the month and day, dawn times ranged between 6 and 7 am, and dusk varied between 6 and 8 pm.

Day of the Week

Preliminary evaluations indicate that speeds vary by the day of the week, and perhaps by whether the day was a weekday or a weekend. The research team examined whether the day of the week could be grouped into three types: weekdays (Monday to Thursday), Friday, weekend (Saturday and Sunday). The speeds exhibit similar behavior on most of the weekdays with a different trend on Fridays for most of the sites. Saturday and Sunday general had lower speeds as compared to weekdays. Some of the analyses considered day of the week and other day type to explore if one variable was superior over the other.

Crowdsourced Segment Length

The crowdsourced speeds are determined using the travel time from one sensor to the next. The distance between these sensors could influence the speed measurement, primarily depending upon roadway characteristics such as the number of signals or driveways. Table 2 shows the length of each segment.

Preparation of the Databases

The data as discussed in the previous section were fused together to obtain two databases used in the analyses. For the analysis of the relationships between roadway characteristics and operating speed, the collected bicycle data were merged with road tube data using site identification number and time stamps. The road tube data (vehicle speed and volume data) were merged with bicycle data using two separate temporal matching criteria:

- Priority 1: Exact 15-minute binned temporal matching of the bicycle data and road tube data.
- Priority 2: Due to the unavailability of 2017 bicycle count data at SD01-NB, SD01-SB, and SD02-SB, similar days of the week of the same months of 2016 were matched for 15-minute bins.

The matched bicycle count data / vehicle speed and count data were fused with the roadway geometry and traffic control device data using site identification number. Out of 18,816 potential 15-minute bins, 113 records do not have speed data entries because they occurred late night or very early morning when no vehicles were present within the 15-minute period. These records were removed from the final analysis. This dataset contains 18,703 15-minute binned traffic volume, speed, bicycle volume, and related geometrics/traffic control device information.

For the analysis of how crowdsourced data could be used to estimate uncongested speed, the research team matched the on-road tube data and the crowdsourced data by site using date and start time for the time increment and the geometric and TCD data were matched using the site number. For the crowdsourced data analysis, data for Sites 1, 2, 4, 5, and 8 were available providing a total of 12,096 15-min periods for evaluation. The research team then eliminated the 15-minute periods where no vehicles were recorded (68 records, most of which occurred at night or early morning on a Sunday), thus resulting in a total of 12,028 15-min periods available.

Results: Influences on Vehicle Operating Speed

Exploratory Data Analysis

Figure 1 shows the relationships between three key measures (average vehicle speed, vehicle volume per lane, and bicycle volume) by the time of day. Unsurprisingly, bicycle volumes are higher during the daytime. For roadways with 40.3 km/hr [25 mph] posted speed limit, the peak of the bicyclist volume happened between 9 am to 11 am, and 6 pm to 7 pm. The distribution of the average speeds within these two time intervals are lower compared to other time intervals. This pattern is not steadily visible in the morning peak hours for the roadways with 72.5 km/hr [45 mph] posted speed limit. For the evening peak (6 pm to 7 pm), lower average speeds of the vehicles are visible. It is important to note that vehicle operating speed is also associated with vehicle volumes per lane. For roadways with 40.3 km/hr [25 mph] posted speed limit, higher vehicle volumes are visible at evening peak. For both the morning peak and evening peak hours, vehicle volumes are visibly higher for roadways with 72.5 km/hr [45 mph] speed limit.

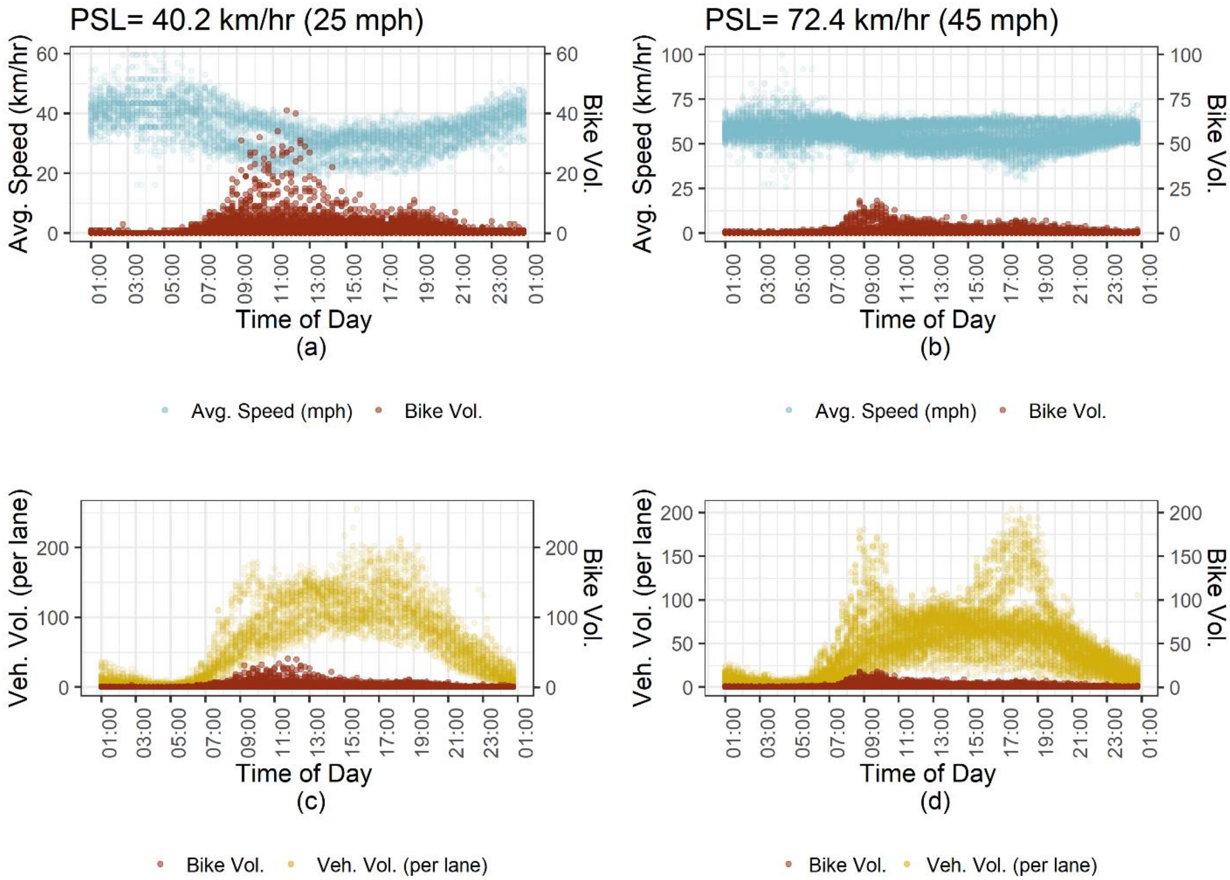


Figure 1. Relationship between three key measures for different time of day.

Figure 2 shows a series of the violin and box plots, which illustrate additional details of the key three measures per location. As 15-minute binned bicycle volumes contain the significant number of zero counts, the violin and box plots were generated for hourly volume (both bicycle and vehicle) counts instead of 15-minute binned counts. The median speeds for all segments show lower average speeds than the posted speed limits. It is not surprising due to the higher volumes on urban arterial roadways. The median values of vehicle volumes are higher in four sites (Sites 1, 2, 4, and 5) compared to other sites. The roadway segment with 40.3 km/hr [25 mph] posted speed limit shows the higher median number of bicycle volume compared to the roadway segments with 72.5 km/hr [45 mph] posted speed limit.

The research team also used NOAA hourly precipitation data to observe the impact of precipitation and found that there was no major influence of precipitation on the data included in the dataset. As the majority of the timestamps contain zero bicycle counts, three evaluations were conducted. The first used all available 15-minute periods with on-road speed data when the vehicle count was not zero. This dataset had 18,703 15-minute periods. The next two models used 15-minute periods when bicycle counts are available and reflected the two available posted speed limits. Addition filters for these two models were that only daytime data were included and bicycle volume per 15-

min binned was greater than 1. This final dataset contains 2,435 15-minute periods for analysis (1622 for 25 mph roadways, and 813 for 45 mph roadways). After performing a preliminary analysis, it was found that effect of the number of signalized intersections is unpredictable and random.

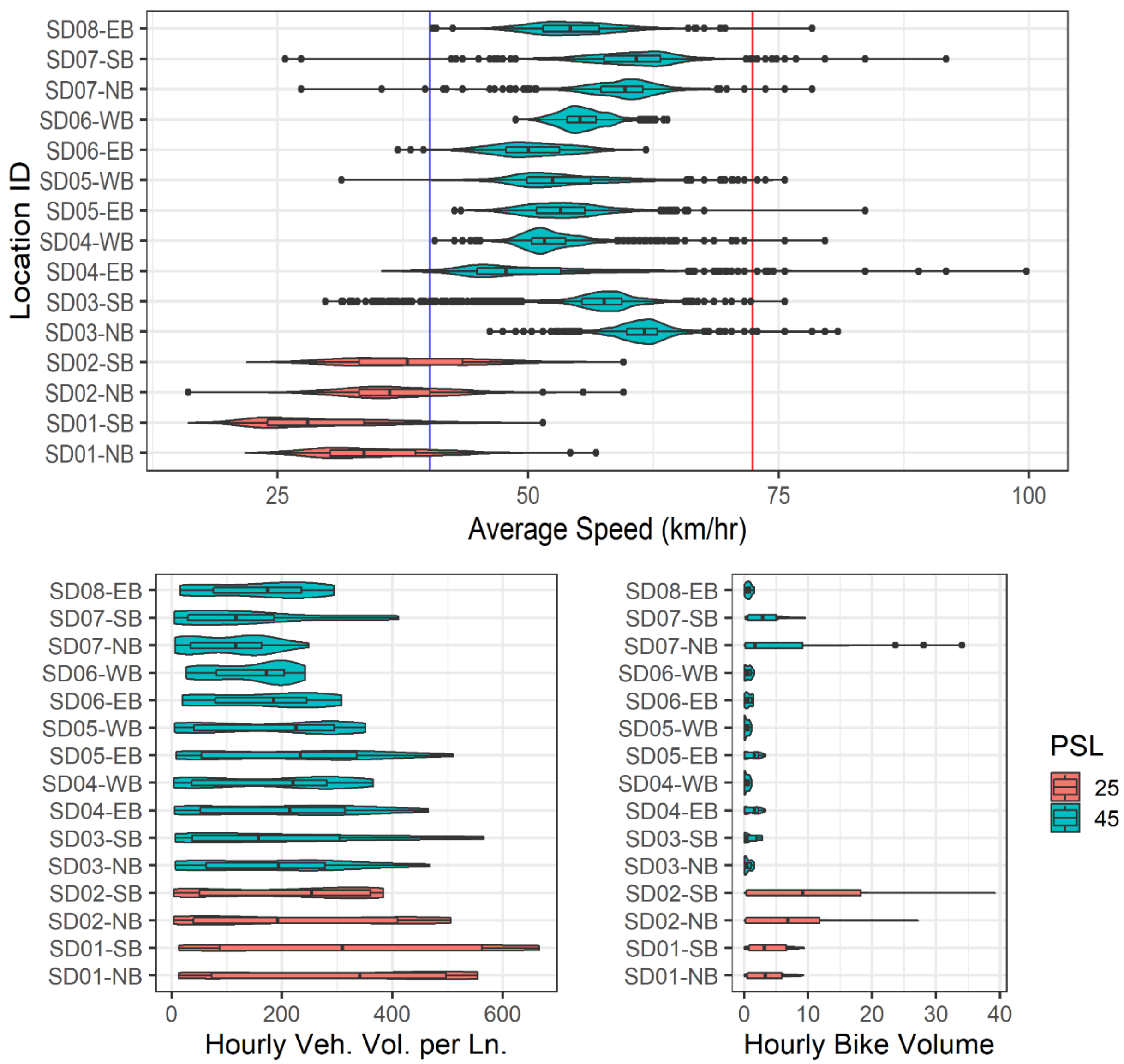


Figure 2. Violin and box plot distribution of three key measures per location id.

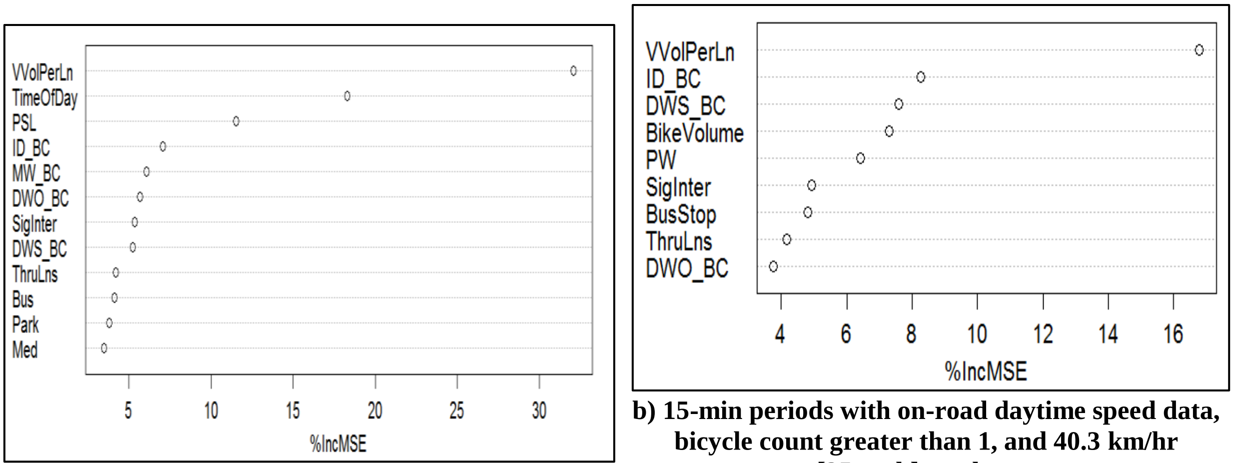
Model Development

The linear regression model is one of the most common modeling technique used in transportation engineering. This model is applied when there is a linear association between the response variable and exploratory variables. In a linear model, the exploratory variables are considered as fixed effect variables. In the real world, many relationships are not systematic like linear model assumptions.

By considering a random effect in the modeling framework, it is possible to characterize the distinctive variation due to the individual differences. Random effects are something that is usually non-systematic and unpredictable and bring random influence on the data. Consideration of both fixed and random effect in the modeling framework is known as mixed effect modeling. Several linear mixed models were developed; some focusing on using all available speed data and others focusing on when more than two bicyclists were present within the 15-minute period. Other attempted split the data by the different posted speeds.

The importance of the variables was ranked by using random forest (RF) algorithms. The RF method is based on the bagging principle and random subspace method that relies on constructing a collection of decision trees with random predictors. Variable importance ranking is measured by the classification accuracy and Gini impurity. This importance measure shows how much the mean squared error or the “impurity” increases when the specified variable is randomly permuted. If prediction error does not change by permuting the variable then the importance measures will not be altered significantly which in turn will change the mean squared error (MSE) of the variable only slightly (low values). This implies that the specified variable is not important. On the contrary, if the MSE significantly decreases during the permutation of the variable then the variable is deemed as important.

By keeping 15-min binned average speed as the dependent variable, the random forest algorithm was applied in developing the variable importance measures. Figure 3 illustrates the dot chart of variable importance as measured by the algorithm. This plot allows how each of the variables contributes to decrease ‘no impurity’ on average. The more a variable contributes, the more significant it is. A threshold of 5% MSE was applied in determining the final list of variables. The variable importance measure shows that the vehicle volume per lane (VVolPerLn) is the most influential variable for all three cases examined. Other variables considered are: time of day (day/night/dawn/dusk), posted speed limit (PSL), distance between counter location and feature that could be influencing the on-road speed measurement adjusted to base condition (ID_BC), number of driveways along the same side of the road as the travel direction adjusted to base condition (DWS_BC), number of driveways along the opposite side of the road as the travel direction adjusted to base condition (DWO_BC), bicycle volume (BikeVolume), presence of on-street parking (Park), on-street parking width (PW), number of signals (SigInter), presence of bus stop (BusStop), presence of raised median (MED), median width adjusted to base condition (MW_BC), and number of through lanes (ThruLns).



a) all 15-minute periods with on-road speed data

b) 15-min periods with on-road daytime speed data, bicycle count greater than 1, and 40.3 km/hr [25 mph] roadways

Figure 3. Variable importance plots.

Model Results

Model Based on All Available On-Road Speed Data

The top nine variables are shown in Figure 3(a) explain at least 5% of IncMSE. These variables are considered for primary analysis to identify variables influencing operating speed on an arterial. After performing a preliminary analysis, the number of through lanes and median width are found to be unpredictable and "random" and both were considered as random-effect variables. Table 3 shows two models with Model 2 removing the number of signals since it was found to be not significant in Model 1. The variables found to influence operating speed included the number of vehicles within the 15-minute period, the distance the counter was from a signalized intersection or a roundabout, the number of driveways (access density), and the posted speed limit. Nighttime speeds were not significantly different from daytime speeds. While dawn and dusk speeds were significantly different from daytime speed, the amount of difference was small and could be considered to be not of practical difference.

Table 3. Model Outputs for 15-Minute Periods with On-Road Speed Data

Variable	Model 1				Model 2			
	Estimate	Std. Err.	t-stat	p-value	Estimate	Std. Err.	t-stat	p-value
Fixed Effect Variables								
Intercept	19.7490	3.2862	6.0097	0.0000	21.0073	1.6141	13.0146	0.0000
Vehicle volume per lane	-0.0477	0.0007	-68.076	0.0000	-0.0477	0.0007	-68.077	0.0000
Influence distance-base condition (ft)	0.0225	0.0005	42.5667	0.0000	0.0225	0.0005	42.5696	0.0000
Driveway density same direction-base condition	-0.1646	0.0375	-4.3897	0.0000	-0.1484	0.0057	-25.933	0.0000
Driveway density opposite direction-base condition	-0.0844	0.0373	-2.2622	0.0237	-0.0682	0.0042	-16.255	0.0000
Number of signalized intersections	0.5020	1.1496	0.4367	0.6623	--	--	--	--
Night	0.0574	0.0587	0.9781	0.3280	0.0573	0.0587	0.9772	0.3285
Dawn	0.4621	0.1035	4.4662	0.0000	0.4621	0.1035	4.4658	0.0000
Dusk	-0.2281	0.0959	-2.3791	0.0174	-0.2281	0.0959	-2.3792	0.0174
PSL=72.5 km/hr [45 mph]	6.8558	0.8194	8.3670	0.0000	7.2117	0.0772	93.4674	0.0000
Random Effect Variables								
Intercept (Median width-base condition)	9.86 (3.14)				10.33 (3.21)			
Intercept (Number of Through lanes)	0.05 (0.01)				0.04 (0.01)			
Residual	6.58 (2.57)				6.58 (2.57)			
AIC	88,374.9				88,373.1			
BIC	88,476.7				88,467.1			
Log likelihood	-44,174.4				-44,174.5			
Deviance	88,348.9				88,349.1			

Models Focusing on When Bicycle Counts are Available

The next set of models used data when more than one bicyclist was present within a 15-minute period and the light condition was daytime. The research team attempted to develop models using both posted speed limits and then by each posted speed limit. The attempts using the 72.5 km/hr [45 mph] speed limit data resulted in models with bicycle volume being not significant. This is not surprising given that the range of bicycle volume available for the higher speed roads is limited, for most of the sites, less than five bicyclists were observed in an hour (see Figure 2).

The model using data for the 40.3 km/hr [25 mph] roadways demonstrates that vehicle volume per lane and bicycle volume are statistically significant and are negatively associated with vehicle operating speed (see Table 4). An increase of 19 motor vehicles per 15-min binned will decrease average speed by 1.6 km/hr [1.0 mph]. For bicyclists to have a similar impact on operating speed, the model indicates that more than 39 bicyclists per 15-min period is needed. For this dataset, a maximum of 41 bicyclists was observed in a 15-minute period; therefore, whether larger number of bicyclists will have a greater influence on operating speed cannot be determined within this study. An increase of 30.5 m [100-ft] influence distance will increase average speed by 5.0 km/hr [3.1 mph]. Presence of bus stop is associated with a decrease of speed by 6.4 km/hr [4.0 mph]. Driveway density is not significant for this model.

Table 4. Model Outputs for 15-Minute Periods during Daylight Conditions and More than One Bicyclist

Variable	**Model for 40.3 km/hr [25 mph] roadways**			
	Estimate	**Std. Err.**	**t-stat**	**p-value**
Fixed Effect Variables				
Intercept	22.2879	0.2361	94.4009	0.0000
Vehicle volume per lane	-0.0523	0.0015	-34.5227	0.0000
Bicycle volume	-0.0254	0.0101	-2.5099	0.0121
Influence distance-base condition (ft)	0.0311	0.0016	19.4409	0.0000
BusStop=Yes	-4.0076	0.3376	-11.8725	0.0000
Random Effect Variable				
Number of signalized intersections				
Intercept	0.23 (0.01)			
Residual	2.98 (1.73)			
AIC	6,390.7			
BIC	6,433.8			
Log likelihood	-3,187.3			
Deviance	6,374.7			

Results: Crowdsourced Data

Exploratory Data Analysis

The preliminary analysis involved visual inspection of patterns. A review of the distribution of average 15-minute speed by vehicle volume shows the expected pattern of average speed being lower for the higher volumes. The speed ranges for each site is shown in Figure 4, which illustrates the difference in speeds, based upon how they measured.

To explore the relationship between tube speed data and crowdsourced speed data, the research team calculated a new variable, TMCS, which is the speed difference between tube and crowdsourced speeds. Figure 5 shows the variation of TMCS based on the day of the week. In most cases, TMCS is positive; indicating that the tube speed data is greater than the crowdsourced data.

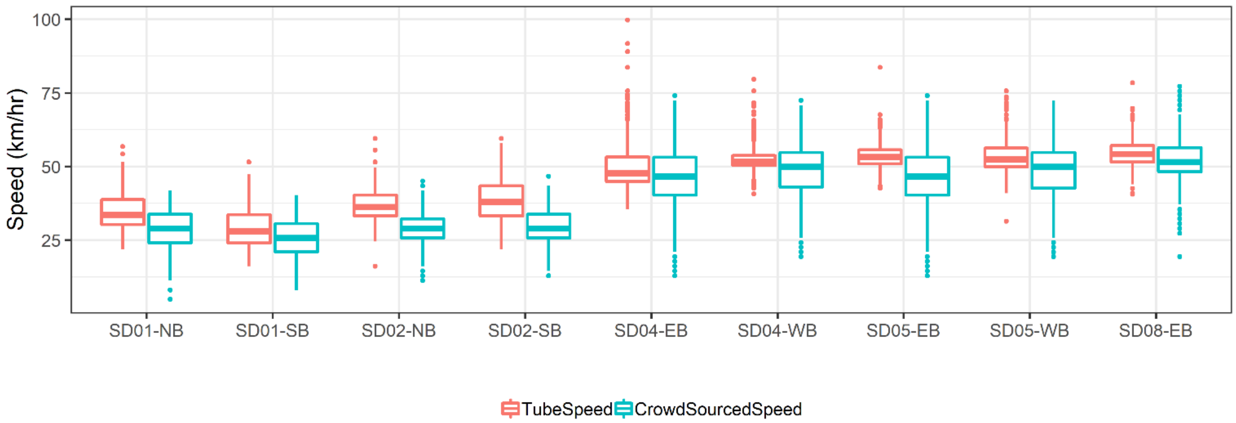


Figure 4. Box plot for tube and crowdsourced speeds at each site.

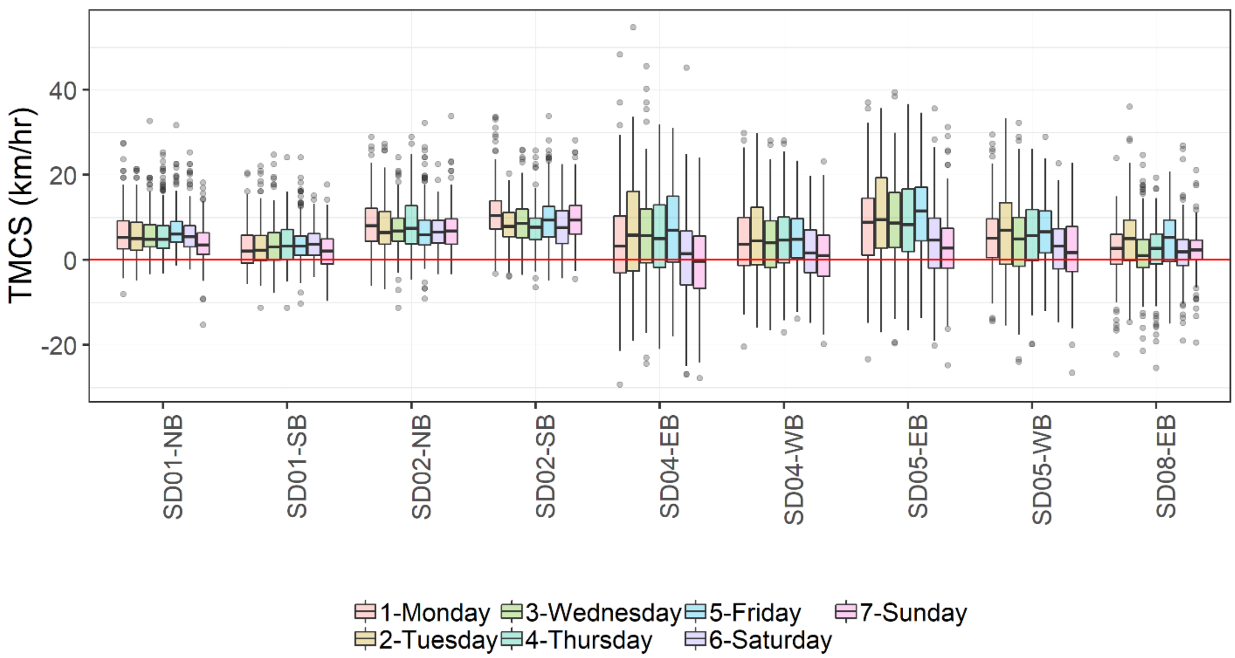


Figure 5. Speed difference variation per site for each day.

Operational Analysis

The evaluation used a decision tree approach to determine which variables are most associated with small differences between tube speed data and crowdsourced speed data (i.e., TMCS). A decision tree has the appearance of a flow chart where each node represents the test on the variable (e.g., number of signals is less than 4) and the branches represent the outcome of that test. In the number of signals example, the branches would show the mean TMCS value when yes (the number of signals is 4 or less) or no (the number of signals is greater than 4).

The research team adopted a rule fit method to obtain hidden rules for predicting the importance of selected variables from a pool, which contains ranges of the factors using "rule generation" and "rule pruning" algorithms. The rule-based analysis can handle large dataset with a mixture of variables, ranging from numeric to categorical and resulting in easy interpretation. Rule based-decision trees are derived for the database by considering all parameters to intuitive parameters, which eliminate lower significant variables.

The research team used different subsets of the available variables to explore the characteristics that could be affecting the results. This work permits the opportunity to identify whether a subset of variables could be considered appropriate for estimating an arterial performance. Several approaches were explored as part of the research, and this report documents the two approaches with the most interesting findings. The first approach focused on roadway characteristics. The variables considered included: number of signals, number of through lanes, the distance between the tubes and nearest signalized or roundabout intersection, median width, number of driveways, posted speed limit, and segment length. The other approach focused on uncongested periods, i.e., LOS A, B, and C. Previous research has defined uncongested conditions as being LOS A, B, or C, so those categories were included in this evaluation.

Figure 6 shows the results when only considering geometric variables. The analysis revealed that the most influential variable is the number of signals. Smaller differences between the crowdsourced speeds and the on-road tube speeds are present when there are few signals within the corridor; in this dataset, less than 4 signals within the corridor had better matches. Signals are associated with large disruptions in travel and can introduce delay within the corridor; therefore, it is logical that the number of signals needs to be considered when using crowdsourced data as a representative speed for a specific location. The next influential geometric variable was the number of driveways. Similar to the signals, driveways can introduce conflicts within the travel stream. A vehicle slowing to turn right at a driveway can increase the travel time for other vehicles. While a vehicle turning out of a driveway should wait for an adequate gap, experience has shown that drivers may turn onto the major roadway anticipating that major street drivers will slow to avoid a crash. The more driveways the greater the likelihood that delay will be added to the time to travel from one end of the corridor to the other, thus resulting in potentially a greater difference between crowdsourced data and speeds measured at a specific location.

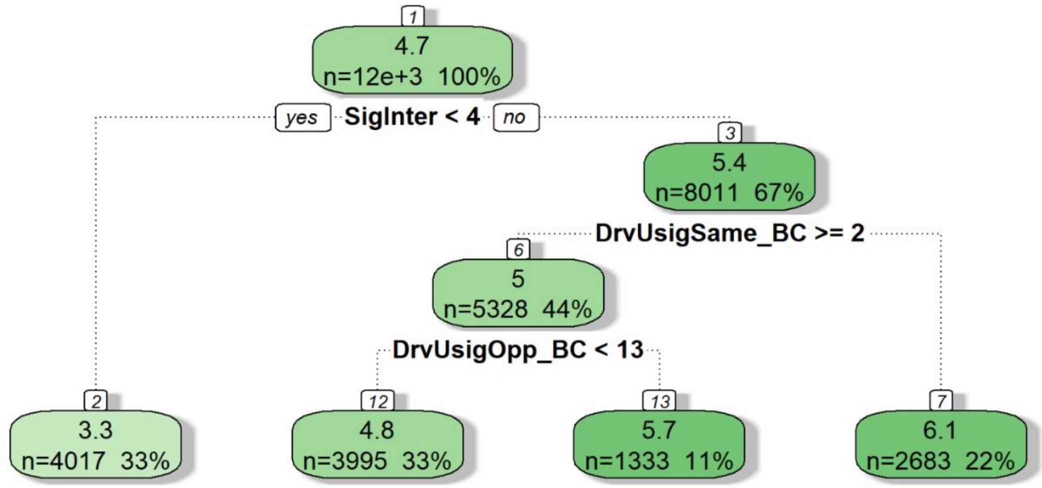


Figure 6. Decision tree for speed difference using only geometric variables.

The decision tree shown in Figure 7 focuses on temporal variables such as the day of week and the light level with the added restriction of only including the 15-min periods when LOS A, B, or C (as determined from the tube data) is present. This analysis may help with the question on which conditions could be used to approximate the speed during uncongested conditions. The analysis found the smallest difference between the crowdsourced speed and tube speed is during Saturday and Sunday.

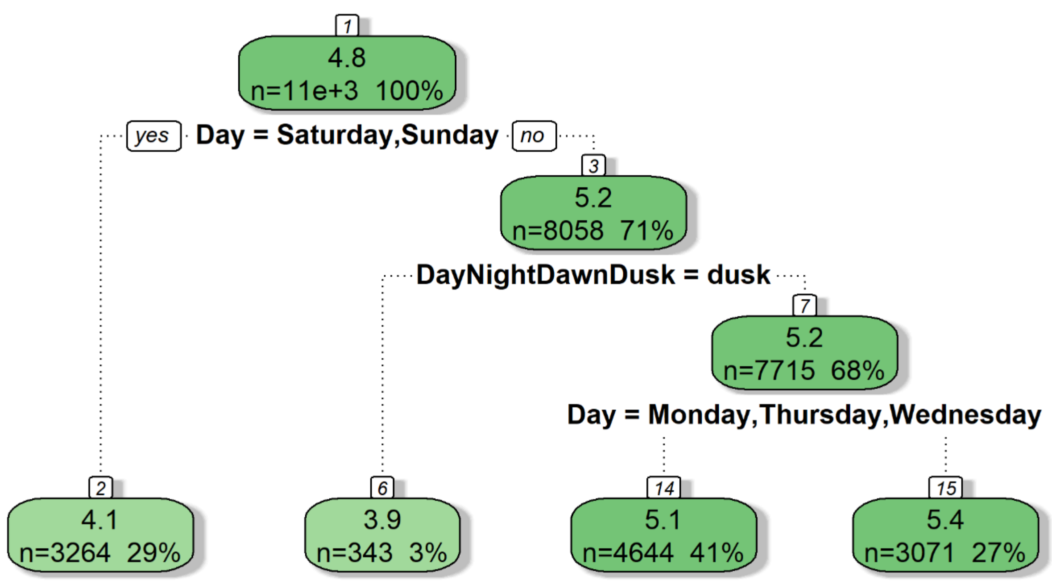


Figure 7. Decision tree for speed difference using temporal variables when only considering those 15-min periods when LOS A, B, or C is present.

Conclusions and Recommendations

Bike Count Data

As part of this research, the research team explored the relationship between vehicle operating speeds with urban arterial street characteristics, with a focus on bicycle count data using linear mixed effect modeling. Both vehicle volume per lane and bicycle volume were found to be influential in influencing average speed on lower speed urban arterial roadways. For 40.3 km/hr [25 mph] sites, an increase of 19 motor vehicles per 15-min binned will decrease average speed by 1.6 km/hr [1.0 mph]. For bicyclists to have a similar impact on operating speed, the model indicates that more than 39 bicyclists per 15-min period is needed. For this dataset, a maximum of 41 bicyclists was observed in a 15-minute period; therefore, whether larger numbers of bicyclists will have a greater influence on operating speed cannot be determined within this study.

Because of the limited number of 15-min periods with bicycle counts greater than 1, the research team also developed a model using all available 15-min periods with on-road speed data. The variables found that influence operating speed include vehicle volume per lane, distance between counter location and feature that could affect speed (typically a signalized intersection), median width, number of driveways and number of signals 0.8 km [0.5 mi] on either side of the counter location, posted speed limit, and light condition (day, night, dawn, dusk).

Crowdsourced Data

The objective of the evaluation of the crowdsourced data was to identify if there are specific conditions when crowdsourced speeds on an arterial could appropriately reflect the speed at a specific location. Crowdsourced speeds reflect a corridor speed and may need adjustments to be able to adequately reflect the speed at a specific location within the corridor. Speed and volume data in 15-minute increments for two weeks at nine sites were obtained using on-road tubes and from a vendor who sells crowdsourced speed data. These data streams were fused using the site number, date, and time for each of the 15-min periods. The difference between the tube data and the crowdsourced data was calculated and called TMCS. The research team conducted the analysis using decision trees to identify those variables most associated with the smallest values of TMCS.

The geometric variables that had the greatest influence on TMCS were the number of signals and the number of driveways within a corridor. Those corridors with a smaller number of signals (less than 4) and a smaller number of driveways (less than 13) were associated with smaller values of TMCS. When focusing on variables associated with a specific 15-min period, congested periods (level of service D or E) were associated with the smallest TMCS values. When only including non-congested periods (i.e., level of service A, B, or C), weekends (Saturday or Sunday) were associated with the smallest TMCS.

Challenges and Future Research Needs

The success of this research effort relied on several components including the availability of the needed data along with the ability to fuse these data streams. While bicyclists are counted in several locations, many are on trails, which was not the focus of this study. When the counters were on an arterial street, they were frequently located near a signalized intersection or a roundabout, which affects vehicle operating speed. Sites were selected to maximize the number of bicyclist; however, a smaller range of bicycle volume was available than desired, especially for higher speed streets. Another challenge was that even though the selected sites had sufficient battery life (indicating that future bicycle counts are possible), three sites did not have bicycle data to match to the on-road speed measurements conducted after the sites were selected. Previous years bicycle counts had to be considered at those sites.

With the growing number of cities adding a bicycle count program, future studies may be able to assemble a larger sample size with a wider variety of arterial roadway features. Another approach could be to include additional measures (bicycle speed and lateral distances between vehicles and bicyclists) to determine the robust quantification of average vehicle speeds in presence of the bicyclists.

With respect to the crowdsourced study, the crowdsourced data included several empty cells. It also does not include vehicle volume for the given time period, which is a significant limitation for this type of research. Future studies with a larger sample size of sites and tube data with individual vehicle speed could provide better estimates of the relationship between spot speeds and corridor speeds as provided by crowdsourced data.

Additional Products

The Safe-D website with information about this research is at: https://www.vtti.vt.edu/utc/safe-d/index.php/projects/influences-on-bicyclists-and-motor-vehicles-operating-speed-within-a-corridor/.

Education and Workforce Development Products

The EWD efforts included the following:

- Providing the TAMU Civil Engineering professors the results from this research so they can incorporate into their courses, as appropriate.
- Made presentation on the findings from the research at the ITE Joint Meeting of the Western District and the Texas District in June 2018. Hope to make presentation on findings at the 2019 TRB Annual Meeting (decision of the paper reviewers to be made by late October 2018).
- Three students assisted with this research: Manaswini Condor (graduate student but did not use topic for engineering paper), Marie Connie Rodriquez (undergraduate student), and Elizabeth Clark (summer intern).
- Obtained enrichment statement from one of the students associated with the project (see below).

Statement

What I like the most about this project is knowing that I am contributing to a research effort that has the potential to make roads safer for bicyclists. Riding a bicycle as a form of transportation is better for the environment and is also a great exercise. I would like to see more people choosing to ride their bike than driving a car but in order for that to happen roads need to be as safe for cyclist as it is for vehicle drivers. My role in this project was to download, reduce, and analyze the bike volume data which allowed us to find a relationship between the vehicles speed and the bike volume at every 15 minutes. The major challenge that I faced was working with a set of data that was not readily available and sometimes data was unrealistic during certain time periods. The solution was to keep monitoring the data collection website until the data became available and in some cases using historical data. From this I learned that you will not always have a perfect set of data to work with, but you have to the best you can with what you have without compromising the validity of the findings. Overall, I believe working on this project was a great experience and now I am more prepared to face challenges that I may encounter in future research projects.
-Maria C. Rodriguez, 10/17/17

Technology Transfer Products

The following paper was prepared and presented at the June 2018 conference:

> Das, S., K. Fitzpatrick, M. C. (2018) "Effects of Bicyclists on Vehicle Operating Speed: A Study on urban Arterial Roadways," ITE Joint Meeting of the Western District and the Texas District.

The following paper was prepared and submitted for the 2019 TRB Annual Meeting:

Fitzpatrick, K., S. Das. (2019 anticipated) "Using Crowdsourced Data to Estimate Operating Speed on Suburban Arterials," Submitted for consideration for the 2019 TRB Annual Meeting.

Data Products

While similar data were used in both analyses, there are cases where data were only available for certain conditions; therefore, the research team created two databases that matched the two objectives.

- BikeVehAnalysis database is available at INSERT APPROPRIATE LINK TO SAFE-D DATAVERSE). It includes data for 15 sites for the following groups:
    - Vehicle data obtained from on-road tubes for 15-min periods that include number of vehicles within 5 mph bins. Average speed and number of vehicles per lane were calculated from the vehicle counts per 5 mph bin.
    - Bicycle count data obtained from on-road bicycle sensors including whether a direct match with the on-road tube vehicle operating speed was possible (priority 1) or if a previous year bicycle count was matched with the vehicle operating speed (priority 2).
    - Temporal variables associated with the 15-min period such as time (hour), day of week, and light conditions (day, night, dawn, dusk).
    - Site characteristics, such as lane width, number of signals, etc. Table 2 provides a list of the key variables included.
- Crowdsourced Analysis database is available at INSERT APPROPRIATE LINK TO SAFE-D DATAVERSE). It includes data for 9 sites for the following groups:
    - Vehicle data obtained from on-road tubes for 15-min periods that include number of vehicles within 5 mph bins. Average speed and number of vehicles per lane were calculated from the vehicle counts per 5 mph bin.
    - Temporal variables associated with the 15-min period such as time (hour), day of week, and light conditions (day, night, dawn, dusk).
    - Site characteristics, such as lane width, number of signals, etc. Table 2 provides a list of the key variables included.
    - Crowdsourced data obtained from vendor in 15-min periods.

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