


Influence Area at Signalized and Stop-Control Intersections: Operational Analysis

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Abstract

Understanding the influence of intersections on operating conditions along connecting roadway segments is important for the analysis of highway facilities and corridors. This study aims at assessing the influence area at signalized and stop-control intersections along rural corridors. The study used speed as a performance measure in examining the spatial extent of operational effects at intersections. High-fidelity connected vehicle (CV) trajectory data, collected at 11 different sites in Florida, was used in this study. The CV trajectory data consists of individual waypoints that included timestamps and location coordinates along with other attributes. Drivers' speed profiles while driving through the intersection were established and analyzed to determine the length of upstream and downstream influence areas. Quantile regression models were developed to estimate the 50th, 70th, and 85th percentiles of upstream and downstream influence areas separately for signalized and stop-control intersections. Study results indicate that the upstream influence area is longer for a signalized intersection than for a stop-control intersection for comparable segment running speeds. Further, the downstream influence area is significantly longer than the upstream influence area at signalized intersections, and this was consistent at all study sites. Traffic flow level did not have a significant effect on the upstream or downstream influence area; however, midblock running speed, percent heavy vehicles, and facility type (multilane versus two-lane) were found to significantly affect the upstream and downstream influence areas at signalized intersections.

Keywords

traffic operations, capacity, intersection approach, Highway Capacity Manual, rural highways, intersections

On interrupted flow facilities such as urban street networks and non-freeway rural facilities, the need to slow down or stop at intersections affects traffic operations along the adjoining highway segments. In practice, intersections are represented as point locations in a link-node network configuration (1); however, their operational effects extend for some distance on the connecting incoming and outgoing approaches, thus affecting the operational performance of highway segments in the proximity of intersections. Specifically, vehicles may need to stop or slow down as they approach the intersection and then accelerate to the downstream-segment running speed as they exit the intersection (2, 3). Understanding the spatial extent of intersection impacts on connecting approaches is important for an accurate evaluation of operational performance along facilities and corridors consisting of

multiple segments and junctions. For facility-level analysis, the quality-of-service assessment should not only include the physical intersection area, but also the lengths along all approaches that are affected by the intersection, commonly known as the “influence area.”

The effect of intersections on traffic performance along connecting highway segments, while significant, is

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less defined in practice. Specifically, there is little guidance, if any, in the literature for the traffic analyst to appropriately account for the impact of intersections in operational analyses, especially those related to the assessment of performance along extended facilities and corridors. Therefore, this study aims to examine the spatial extent of the operational effect of signalized and stop-control intersections on the connecting approaches in rural environments where facilities normally operate at undersaturated conditions. The study is part of a larger effort to develop procedures for operational analyses along rural facilities and corridors.

Literature Review

The research on the operational effects of intersections on the connecting roadway segments has been very limited to date. The literature review conducted in the course of this research identified only a few studies. The most recent study, conducted in India, attempted to model driver behavior at signalized intersections under heterogeneous traffic conditions. As part of the driver behavior modeling, the authors used 100 GPS trajectories of a test car to determine the upstream spatial extent of intersection impact on the driver's behavior (mainly speed selection), termed as intersection zone of influence (IZOI). The study reported that the upstream IZOI for cars ranges from around 525 ft to 702 ft (around 160.70–214.08 m) (4). Similarly, Chauhan et al. (5) examined a driving cycle for five intersections on an urban corridor. Driving cycle analysis can be used for improving vehicle fuel consumption and emissions reduction. In their study, the researchers considered both upstream and downstream influence areas of intersections including the width of the intersection as an influence zone. The study concluded with a total influence zone of 1050 ft (320 m) for cars at urban intersections (5). In a traffic simulation study, Li and Washburn (2) used the effective upstream and downstream lengths of a signalized intersection to refer to the intersection influence area in their proposed methodology for assessing performance along rural two-lane highway corridors. The authors used the CORSIM traffic simulation tool to calculate these effective lengths and perform the analyses (2). This study built on the work by Yu and Washburn (3), which also performed facility segmentation and defined the operational boundaries for signalized intersections on a rural highway using the traffic simulation software CORSIM and TWOPAS (3).

Apart from signalized intersections, roundabout operational influence areas have been investigated in only a few studies. However, the spatial extent of influence areas at roundabouts may be different as most vehicles do not stop/yield at a rural roundabout because of

lower traffic volumes. Rodegerdts et al. (6) evaluated the performance of roundabout corridors (corridors with closely spaced multiple roundabouts) using travel time as a performance measure. To do so, facility segmentation was performed, and roundabout influence areas were determined. The study used field-collected floating car data from nine roundabout corridors located in different states in the U.S. The researchers found that the mean upstream and downstream influence areas are 311.0 ft and 617 ft, respectively. The study results suggested that the average downstream influence area is approximately twice as long as the average upstream influence area (6). Similarly, a recent study by Raza et al. (7) investigated the influence areas of spatially isolated roundabouts using high-resolution trajectory data from three different roundabout corridors in the U.S. The research study reported upstream influence areas ranging from 407 ft to 627 ft and downstream areas ranging from 446 ft to 874 ft. Additionally, the study developed statistical models to predict upstream and downstream influence areas for the roundabout based on midblock operating speeds (upstream and downstream midblock segments) and the circulating speed within the roundabout (7). Two studies from Europe also assessed the operational impacts of roundabouts. Silva et al. (8) examined driver behavior while traversing a corridor of three double-lane roundabouts in Portugal. The distance between consecutive roundabouts ranged between 1300 ft and 1540 ft (400–470 m). The study site had a posted speed limit of 31.25 mph (50 km/h) and was located in an urban environment. The researchers found that the total influence area of the roundabout, which includes the upstream influence area, the downstream influence area, and the width of the roundabout, was between 1300 ft and 1640 ft (400 and 500 m), with the width/diameter of roundabouts ranging from 185 ft to 210 ft (55–64 m) (8). An older study by Violette and Cardon (9) suggested that the total length of the influence zone of a roundabout including upstream, downstream, and width of the roundabout can be between 600 m and 1000 m (1900 ft and 3280 ft). These relatively high values may partly be because of the higher roadway speed of the rural site used in this study (9). All the aforementioned studies have attempted to identify the spatial extent of operational effects of either signalized intersections or roundabouts, however, each study has certain limitations such as analyzing only urban street intersections instead of rural intersections (4, 5, 8), studies based on traffic simulation instead of empirical data or validation using field data (2, 3), use of very limited data (small sample) in the study (4), heterogeneous traffic condition that includes two- and three-wheel motor vehicles (4, 5), and closely spaced intersections or roundabouts that have overlapped influence areas (5, 6, 10). To address these

Table 1. Summary of Previous Studies

Authors	Intersection control	Urban/rural	Study purpose	Limitations/relevance
Singh et al. (4)	Signal	Urban	Driver behavior	Heterogeneous traffic, urban intersection, a small sample size of 100 trajectories
Chauhan et al. (5)	Signal	Urban	Driving cycle	Heterogeneous traffic, urban intersection, a small sample size
Li and Washburn (2)	Signal	Rural	Operational impact	Simulation only
Yu and Washburn (3)	Signal	Rural	Operational impact	Simulation only
Rodegerdts et al. (6)	Roundabout	Suburban	Operational impact	Roundabouts only, overlapped influence areas at closely spaced roundabouts
Raza et al. (7)	Roundabout	Suburban	Facility segmentation	Roundabouts only
Silva et al. (8)	Roundabout	Urban	Driver behavior	Roundabouts only, urban streets
Violette and Cardon (9)	Roundabout	Rural	Driver behavior	Roundabouts only

limitations, the current study utilized extensive empirical data with multiple sites each for signalized and stop-control intersections on rural highways. Table 1 presents a summary of the reviewed studies that examined the spatial extent of operational impacts of intersections on connecting approaches.

Study Sites and Data Processing

This study used vehicle speed as a performance measure in examining the spatial extent of operational effects of signalized and stop-control intersections. Specifically, the influence area of an intersection starts when a vehicle starts deceleration at the location upstream of the intersection and ends when the vehicle ends acceleration to the running speed of the downstream segment. The following section discusses the study sites and field data used in this investigation.

Signalized Intersection Study Sites

Four signalized intersection sites were selected in Central Florida. They are all located in rural areas as shown in Figure 1. Intersection names along with intersection geo-coordinates are provided below.

1. Yeehaw Junction [27.69971604, -80.90432579]
2. E. Irlo Memorial Hwy at Arthur J Gallagher Blvd [28.191844854249652, -81.15472021880018]
3. FL-520 at Maxim Pkwy [28.513960380069964, -81.06232455557888]
4. FL-46 at N. County Rd 426 [28.73337366038518, -81.11515460683309]

It is important to note that intersection number 1 (Yeehaw Junction) is located near an interchange for Florida's Turnpike toll road (see Figure 2). The distance

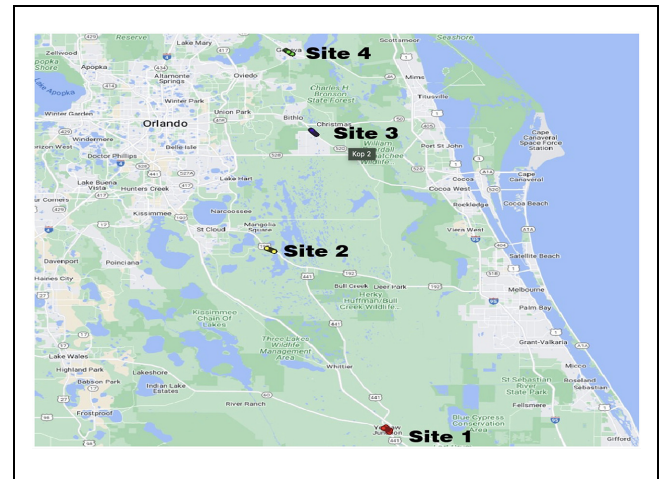


Figure 1. Signalized intersection study sites.



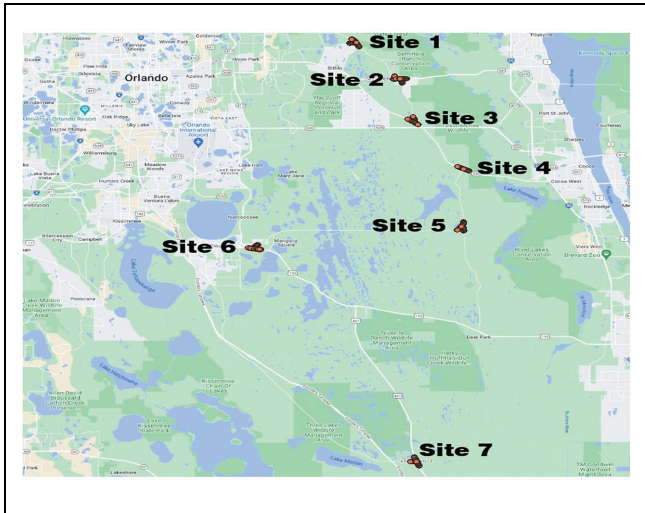
Figure 2. Site 1 signalized intersection.

between the intersection and the interchange is about 875 ft. A high number of heavy vehicles (heavy vehicles constitute around 35% of the annual average daily traffic

Table 2. Sites and Data Summary

Intersection control	Number of sites	Directions (EB/WB or NB/SB)	Approaches	Data resolution frequency (Hz)	Upstream/downstream influence area
Signal control	4	Both	$4 \times 2 = 8$	1/3	Both
Two-way stop control	7	One	$7 \times 1 = 7$	1/3	Upstream

Note: NB = northbound; SB = southbound; EB = eastbound; WB = westbound.

**Figure 3.** Stop-control intersection study sites.

[AADT]) are observed crossing this intersection (using Hwy 60) to and from Florida's Turnpike toll road. This signalized intersection has one lane on each approach and there are no exclusive left or right turning lanes.

Stop-Control Study Sites

To investigate the influence area of stop-control intersections, seven study sites were selected on rural roadways in Central Florida. The stop-control intersections are mostly T-intersections with major uninterrupted highways; therefore, only upstream influence areas on minor approaches were analyzed in this investigation. The locations of the seven sites are shown in Figure 3. Intersection names along with intersection geocoordinates are provided below.

1. Lake Pickett Rd at N. Fort Christmas Rd [28.59868562737476, -81.07542409814873]
2. Taylor Creek Rd at E. Colonial Dr. [28.53655356333482, -81.01220531644309]
3. S. Fort Christmas Rd at E. Colonial Dr. [28.53683001935565, -81.01789051145427]
4. Taylor Creek Rd at FL-520 [28.462825456163536, -80.99278804104223]

5. Deer Park Rd at Nova Rd [28.282567428223185, -80.92317557563702]
6. Nova Rd at E. Irlo Bronson Memorial Hwy [28.243980091596192, -81.22311904061856]
7. Holopaw Rd (US-441 S) at E. Irlo Bronson Memorial Hwy [28.144799048160237, -81.0761156732036]

Study Data

The study data consisted of high-fidelity connected vehicle (CV) trajectory data collected on multiple days (full days) at each study site. These data consist of individual vehicle waypoints with a temporal interval of 3 s (frequency 1/3 Hz) and positional accuracy of a 4.90 ft (1.5 m) radius (11). Every waypoint has the following attributes:

- unique trajectory ID
- timestamp
- latitude/longitude
- speed
- heading angle

The upstream and downstream approaches of the intersection were geofenced for 3000 ft in each direction (total 6000 ft length in one direction). The summary of all sites and data is presented in Table 2.

Data Processing and Reduction

The raw data processing involved program development in MATLAB (12) and the use of QGIS software (13) for cleaning the data. The coordinates of the raw data (in latitude and longitude) were transformed to Universal Transverse Mercator (UTM) coordinates, to get X-Y location coordinates in meters (instead of degrees), which was required for distance computation. The CV data, which consists of waypoints per 3 s, were converted to a complete trajectory of waypoints based on the unique trajectory ID. Cleaning the data consisted of removing trajectories with missing points and short trajectories of less than 10 waypoints. Next, the trajectories were separated based on the direction of travel at each study site using the heading angle.

Influence Area Determination

For the analysis of the influence area, only the trajectory data for vehicles that stopped at the intersection were considered. Vehicles that traversed the intersection without stopping were not included in the analysis as they were not much affected by traffic control. Once the GPS data transformation and processing had been conducted, a four-step heuristic algorithm was developed to identify the start and end of the upstream and downstream influence areas of the intersection, as follows.

- i. *Identify start of upstream influence area:* For upstream influence area and deceleration rate, examine the speed profile and determine the point from which the vehicle speed drops at least 4 feet per second [fps] ($a \leq -4 \text{ fps}^2$) for three consecutive GPS waypoints (i.e., 9 s) and continues decelerating until it stops. Once that point is determined, the distance between the location of the point and the stop line at the intersection approach is calculated. The threshold of a minimum of nine consecutive seconds was selected to include all speed profiles in the analysis, even those with high deceleration rates and short stopping distances.
- ii. *Identify end of downstream influence area:* For the downstream influence area, the speed profile is examined beyond the minimum speed location near the stop line. The end of the acceleration or downstream influence area is identified when the speed increase for two consecutive GPS waypoints (i.e., 6 s) becomes less than 1 fps^2 . Step *i* and Step *ii* are presented in Figure 4.
- iii. *Determine upstream influence area length:* For a stopped vehicle in a queue, the upstream influence area is the distance between the starting point of deceleration determined in Step *i* and the location when vehicle speed reaches zero plus the distance from the stop line.
- iv. *Determine downstream influence area length:* For a vehicle that is stopped upstream of the stop line at the intersection approach, the downstream influence area is the distance between the location of the stopped vehicle and the endpoint of the downstream influence area determined in Step *ii* minus the width of intersection and the distance between the stopped vehicle and the stop line (zero for the first vehicle in a queue).

Data Analysis and Results

After identifying the upstream and downstream influence areas, a detailed analysis was conducted separately at

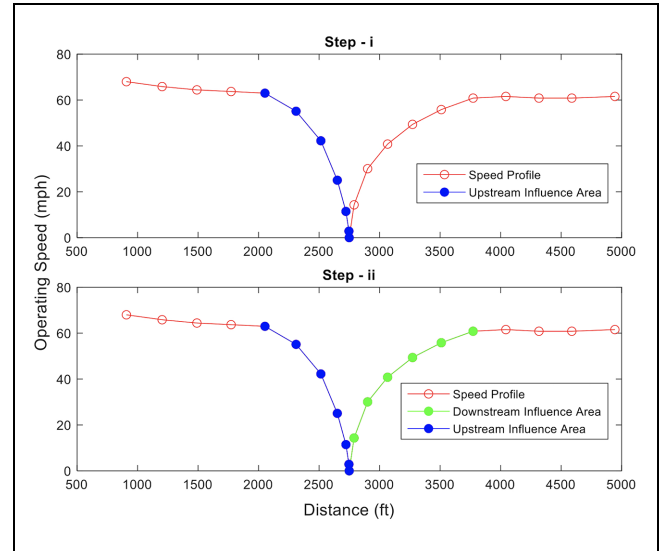


Figure 4. Sample trajectory: upstream and downstream influence area of signalized intersection based on speed profile.

each site for the two traffic control types; signal control and stop control. The influence area data were examined for outliers based on Tukey's (14) interquartile range (IQR) technique. The IQR method is less sensitive to extreme values and is robust against any deviation from a normal distribution of data because it uses quartiles that are resistant to extreme values and therefore can be applied to both normal and skewed distributions efficiently (15). According to the IQR rule, any value that falls below the 25th percentile minus $1.5 \times \text{IQR}$ or above the 75th percentile plus $1.5 \times \text{IQR}$ is considered an outlier. Unless specified, the discussions in the following sections all refer to the data on excluding outliers.

Preliminary Analysis

This section characterizes the influence area at signalized and stop-control intersections, respectively.

The descriptive statistics of the upstream influence area at the signalized intersection sites are presented in Table 3. The table summarizes the sample size, mean, standard deviation, 50th percentile, and 85th percentiles of upstream influence areas as well as the running speeds on the upstream approach segment for each of the four study sites. The results show that the average influence areas are close to the 50th percentile influence area lengths, which may suggest a largely normal distribution for the influence area length. Furthermore, the results are consistent with the expectation that higher running speeds on the upstream segment result in longer influence areas because of increased stopping distance.

For Site 1, the results indicate that the average influence areas of the first three approaches are longer

Table 3. Upstream Influence Area at Signalized Intersection

Site	Bound	No.	Mean IA ft (speed mph)	SD IA ft (speed mph)	50th Percentile IA ft (speed mph)	85th Percentile IA ft (speed mph)
01	NB	56	1239.10 (62.00)	356.68 (8.27)	1223.30 (63.70)	1684.60 (69.58)
	SB	103	1443.40 (64.15)	398.51 (8.64)	1391.90 (62.99)	1869.40 (72.33)
	EB	303	1056.80 (57.19)	396.94 (9.54)	965.29 (56.55)	1534.90 (68.01)
	WB	509	547.55 (42.84)	202.98 (7.17)	502.95 (42.94)	774.90 (50.11)
02	EB	878	877.52 (61.05)	301.88 (7.13)	835.71 (60.64)	1228.10 (68.01)
	WB	541	799.95 (62.16)	279.48 (7.67)	750.88 (61.56)	1071.10 (70.86)
03	EB	502	867.03 (64.26)	286.60 (6.54)	821.18 (64.42)	1186.10 (70.86)
	WB	544	891.98 (69.85)	305.88 (7.74)	854.06 (69.43)	1205.40 (77.30)
04	NB	593	927.66 (54.38)	315.83 (6.55)	908.80(55.12)	1270.60 (60.52)
	SB	644	761.84 (49.57)	208.92 (5.56)	739.40 (49.39)	975.55 (55.83)

Note: IA = influence area; NB = northbound; SB = southbound; EB = eastbound; WB = westbound; SD = standard deviation.

Table 4. Downstream Influence Area at Signalized Intersection

Site	Bound	No.	Mean IA ft (speed mph)	SD IA ft (speed mph)	50th Percentile IA ft (speed mph)	85th Percentile IA ft (speed mph)
01	NB	48	1716.90 (63.36)	546.99 (10.29)	1850.0 (64.42)	2270.70 (73.94)
	SB	100	1798.10 (62.20)	436.52 (6.27)	1830.80 (62.98)	2252.20 (68.01)
	EB	297	650.80 (42.32)	352.98 (7.22)	542.73 (41.51)	1027.0 (50.11)
	WB	470	1535.80 (58.25)	450.90 (8.26)	1573.20 (58.70)	2057.60 (66.57)
02	EB	881	1469.20 (60.41)	519.46(7.06)	1408.10 (60.12)	2128.80 (68.01)
	WB	557	1224.94 (58.71)	353.25 (6.07)	1187.10 (58.69)	1616.70 (65.14)
03	EB	490	1822.50 (67.01)	459.37 (6.46)	1811.30 (67.28)	2404.01 (73.72)
	WB	515	1538.20 (64.23)	431.58 (6.12)	1498.90 (64.42)	2056.10 (70.15)
04	NB	592	1060.01 (49.69)	342.02 (5.35)	1044.40 (50.11)	1453.60 (55.12)
	SB	651	1267.97 (56.26)	366.07 (5.95)	1324.30 (56.55)	1668.50 (62.27)

Note: NB = northbound; SB = southbound; EB = eastbound; WB = westbound; IA = influence area; SD = standard deviation.

compared with the influence areas of the other sites with similar average running speeds. This may be because of the higher percentage of heavy vehicles (about 35% compared with about 8%–13% at other study sites) and each approach having only one lane, which in turn leads to longer queues. This confirms that the heavy vehicles start decelerating far upstream of the intersection stop line. Furthermore, the standard deviations of influence area lengths at the study sites are relatively high, which could be induced by the higher variation in drivers' behavior and vehicle performance.

For the downstream influence at signalized intersections, the results indicate that the downstream influence areas are notably longer than the upstream influence areas as shown in Table 4. This implies that the deceleration rate upstream of the intersection is higher than the acceleration rate downstream of the intersection even when the vehicle is not impeded. This can partly be explained by the release of vehicles in platoons at the start of the green phase and their acceleration rates being affected by lower-performance vehicles, especially on single-lane highway segments. Further, the uncertainty about the duration of the yellow interval (and the ability to cross the intersection legally) may result in high

deceleration rates for vehicles close to the intersection. Moreover, similar to the upstream influence area for Site 1, the downstream influence areas for the first three departure approaches are longer than the downstream influence areas for other sites with a similar average running speed.

The stop-control intersections investigated in this study are mainly present on minor roads in rural areas with lower traffic volumes and lower posted speed limits compared with the study sites for signalized intersections. Further, all the stop-control intersection study sites are T-type intersections with no downstream through movement, therefore, only the upstream influence area was examined. The results of the stop-control intersections, summarized in Table 5, show that the lengths of the upstream influence areas are considerably shorter compared with the upstream influence areas at signalized intersections. This difference is likely a result of lower speed limits on stop-control approaches and the lack of queues on these approaches because of lower traffic volumes.

The following sections discuss the analysis of different percentile values and the development of statistical models, based on the outcome of percentile analysis, for

Table 5. Upstream Influence Area at Stop-Control Intersection

Site	Bound	No.	Mean IA ft (speed mph)	SD IA ft (speed mph)	50th Percentile IA ft (speed mph)	85th Percentile IA ft (speed mph)
01	EB	131	689.33 (49.62)	255.79 (7.12)	681.50 (48.67)	950.13 (56.54)
02	NB	123	517.28 (44.92)	170.95 (7.54)	482.75 (45.09)	709.75 (52.29)
03	SB	252	735.95 (51.94)	248.08 (7.07)	700.71 (51.89)	1031.20 (59.04)
04	SB	51	599.99 (45.92)	288.35 (7.05)	460.21 (45.09)	999.26 (55.00)
05	NB	20	903.87 (58.94)	309.75 (6.43)	827.90 (59.05)	1289.30 (64.78)
06	SB	22	829.46 (51.24)	309.72 (6.71)	789.79 (50.46)	1205.10 (58.70)
07	NB	526	768.54 (51.62)	210.37 (7.02)	753.15 (52.25)	976.33 (58.69)

Note: NB = northbound; SB = southbound; EB = eastbound; WB = westbound; IA = influence area; SD = standard deviation.

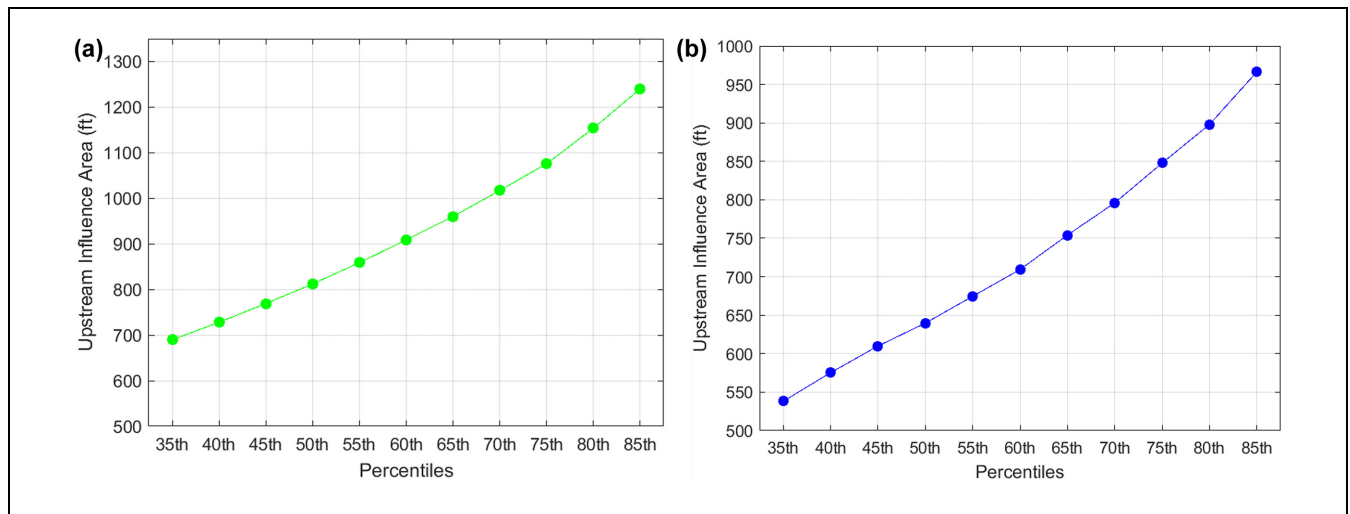


Figure 5. Upstream influence area lengths at different percentiles: (a) signalized intersection and (b) stop-control intersection.

estimating upstream and downstream intersection influence areas for the two types of traffic control.

Percentile Analysis

In transportation engineering, percentiles have been used in practice in many design and safety applications. For instance, it has been an established practice to use the 85th percentile speed as a reference in setting legal speed limits (16). Similarly, the 15th percentile pedestrian walking speed has been used in practice for determining the pedestrian right-of-way time in signal timing design. These are just a couple of examples of using percentiles in safety applications with the objective of making sure that the design incorporates the majority of road users. This section analyzes the percentile influence areas at the study sites to better understand the variation in drivers' braking habits when drivers decelerate or accelerate at the location of intersections. Specifically, conservative drivers may start deceleration farther upstream from the intersection, whereas more aggressive drivers may start deceleration

a short distance upstream from the intersection. Similar variation in drivers' behavior may be observed as drivers accelerate back to running speeds on the downstream segment.

Initially, the trends for the upstream influence area percentile (ranging from 35th to 85th percentiles, in increments of five) are established for the signalized intersection and stop-control intersection, as illustrated in Figure 5. The trendline of the upstream influence area at signalized intersections starts at about 700 ft for the 35th percentile, 810 ft for the 50th percentile, and 1240 ft for the 85th percentile, as shown in Figure 5a. On the other hand, the trendline of the upstream influence areas at the stop-control intersections is relatively low and starts at about 540 ft for the 35th percentile, 640 ft for the 50th percentile, and about 960 ft for the 85th percentile, as shown in Figure 5b.

Using the percentiles' influence area lengths, speed reductions from the upstream running speed to the speed at the location of a specific percentile (influence area) were calculated and plotted as shown in Figure 6. For instance, the average speed reduction from the running

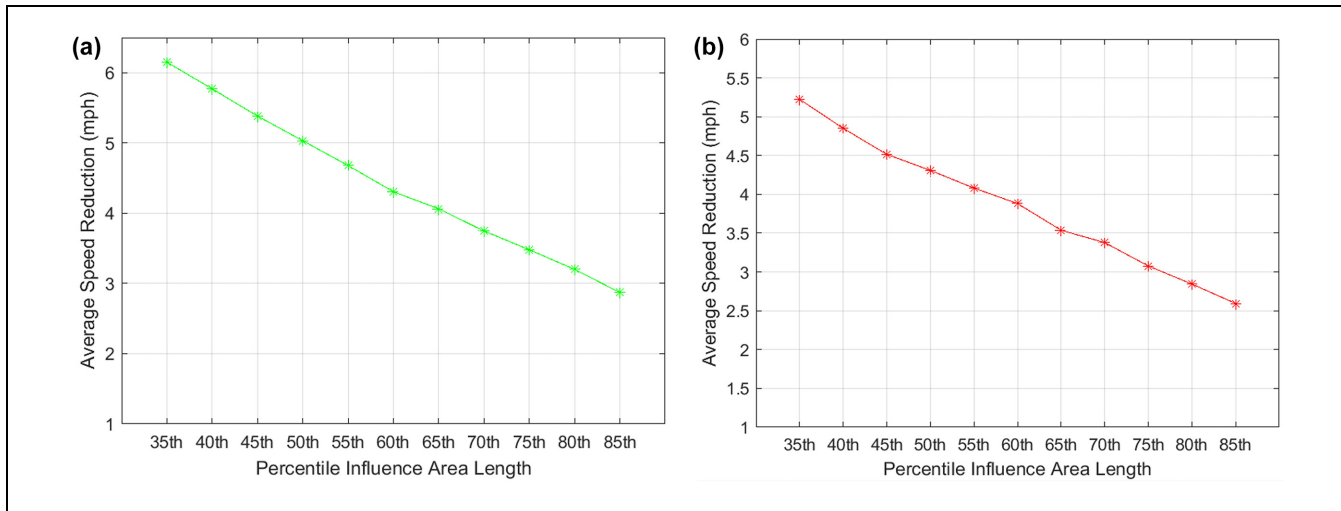


Figure 6. Average speed reduction at upstream influence area: (a) signalized intersection and (b) stop-control intersection.

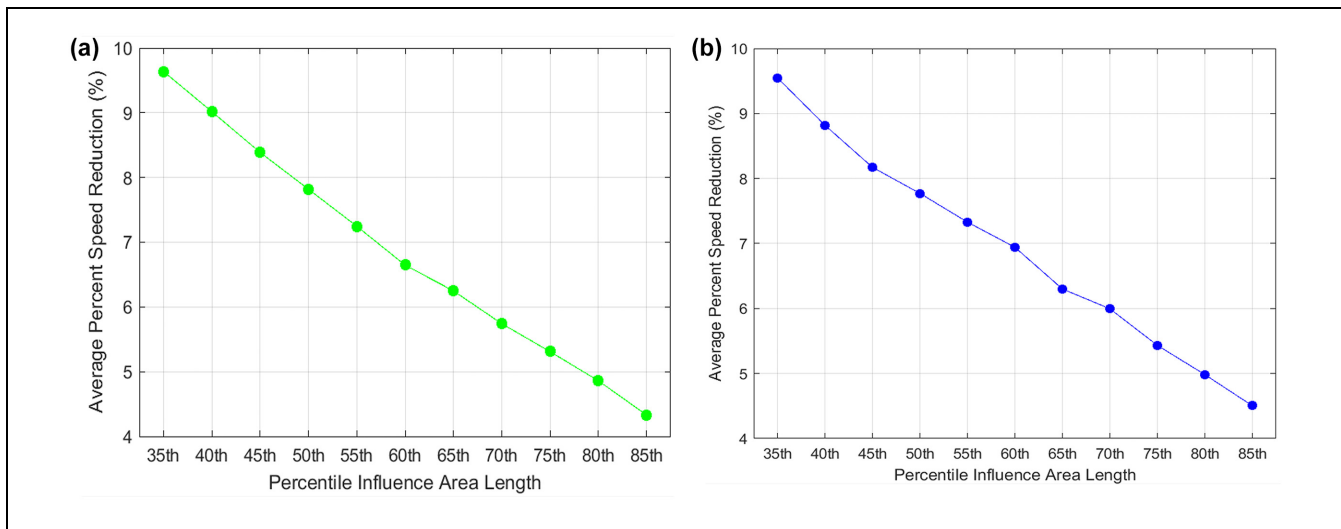


Figure 7. Average percentage speed reduction at upstream influence area: (a) signalized intersection and (b) stop-control intersection.

speed to the position of the 50th percentile influence area length at signal-control study sites is 5 mph, and to the position of the 70th percentile is 3.8 mph, as shown in Figure 6a. Similarly, the average speed reduction from the start of the influence area to the 50th percentile location upstream of the stop-control study sites is about 4.35 mph, whereas at the 70th percentile position, the average speed reduction is about 3.4 mph, as shown in Figure 6b.

As the magnitude of speed reduction in the upstream influence area is primarily a function of the approach running speed, which is different among various study sites, it is important to examine speed reduction as a percentage of approach running speed for comparison purposes. Figure 7 shows the percent speed reduction at

different percentile influence area positions both at the signal-control and stop-control study sites. It is interesting to note that, although the average speed reduction for a given percentile influence area is quite different between the signal-control and stop-control study sites, the percent speed reductions are mostly comparable. For instance, the average percent speed reduction at the location of the 50th percentile upstream influence area is approximately 7.9% both for the signalized and stop-control intersections.

Similar to the upstream influence area, the trendline for the downstream influence area percentiles (ranging from 35th to 85th percentiles, in increments of five) is established for the signalized intersections as shown in Figure 8. The trendline for the downstream influence

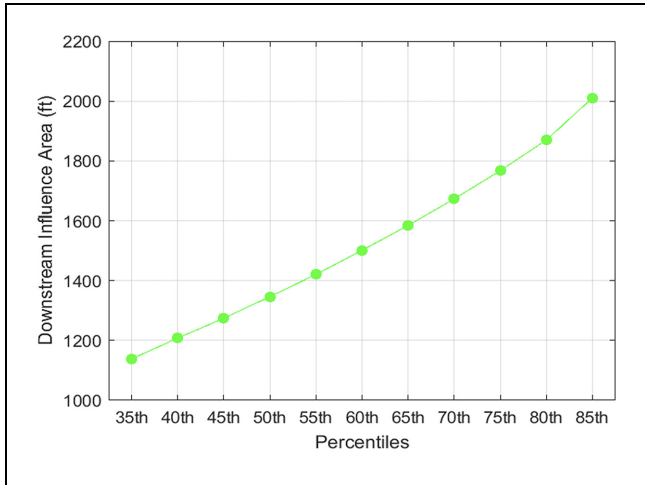


Figure 8. Downstream influence area lengths at signalized intersections for different percentiles.

area at signalized intersections is around 1150 ft for the 35th percentile, 1370 ft for the 50th percentile, and 2000 ft for the 85th percentile, as shown in Figure 8.

Using the percentile influence area lengths, the speed difference from the running speed of the downstream segment to the speed at the location of a specific percentile (downstream influence area) was calculated and plotted as shown in Figure 9a. For instance, the average speed difference between the segment running speed and the speed at the location of the 50th percentile influence area length at signal-control study sites is 6.1 mph, and at the location of the 70th percentile is 4.5 mph, as shown in Figure 9a. Instead of only focusing on the magnitude of

speed difference from the running speed of the downstream segment to the speed at the location of a specific percentile, the average percent speed difference at different percentile influence area locations are calculated and plotted as shown in Figure 9b. Downstream influence areas were not analyzed for stop-control intersections because the stop-control intersections are T-type intersections with no downstream through movement.

Quantile Regression Models

This section discusses the development of statistical models for estimating the upstream and downstream influence areas for the two types of intersection control. The objective is to estimate the influence area using variables that are thought to affect such distance and are readily available to the analyst. Several models were developed and evaluated with different regressors. However, only a few variables such as upstream and downstream segment running speeds, percent heavy vehicles, and facility type (two-lane versus multilane highway) were found to have statistically significant effects on the upstream and downstream influence areas.

The percentile analysis conducted in the previous section allowed us to understand the magnitude of operational impacts (i.e., speed discrepancy) at different influence area percentiles. Consistent with the percentile analysis, the regression models developed and presented in this section help to estimate multiple percentiles of influence area length using some explanatory variables. Specifically, quantile regression (QR) was adopted to model the influence area at the study sites using multiple percentiles. The models enumerate the relationship of

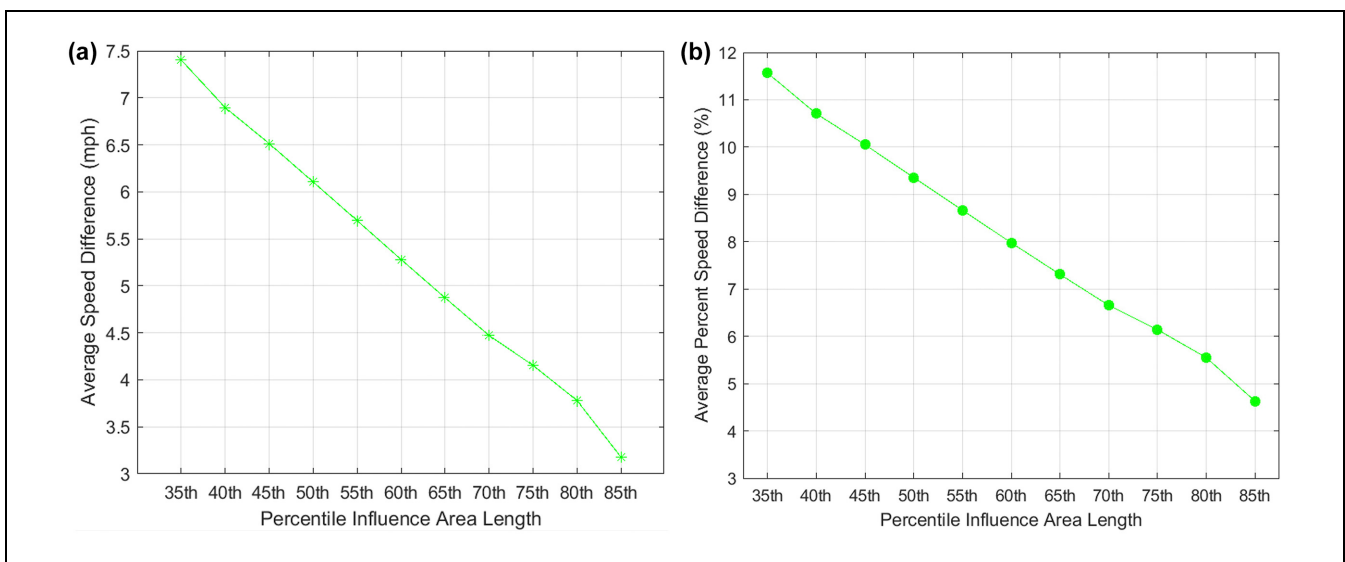


Figure 9. Speed difference for the running speed at downstream segment at signalized intersections: (a) magnitude difference and (b) percentage difference.

Table 6. Linear Quantile Regression Models for Influence Area at Signal-Control Study Sites

Parameters	$\tau = 0.50$		$\tau = 0.70$		$\tau = 0.85$	
	Estimate (SE)	<i>p</i> -value	Estimate (SE)	<i>p</i> -value	Estimate (SE)	<i>p</i> -value
Dependent variable: upstream influence area length (ft)						
Intercept	-364.59 (24.08)	<0.0001	-457.91 (36.44)	<0.0001	-480.58 (46.18)	<0.0001
Upstream running speed (mph)	22.53 (0.41)	<0.0001	25.93 (0.62)	<0.0001	29.02 (0.81)	<0.0001
Heavy vehicle (%)	0.56* (0.48)	0.244	2.55 (0.64)	<0.0001	3.25 (0.74)	<0.0001
Facility type (multilane)	-227.56 (10.70)	<0.0001	-209.38 (15.43)	<0.0001	-225.01 (19.56)	<0.0001
Dependent variable: downstream influence area length (ft)						
Intercept	-1439.59 (43.12)	<0.0001	-1407.53 (50.00)	<0.0001	-1364.49 (47.68)	<0.0001
Downstream running speed (mph)	48.34 (0.75)	<0.0001	50.12 (0.87)	<0.0001	51.24 (0.83)	<0.0001
Heavy vehicle (%)	3.79 (0.69)	<0.0001	5.46 (0.78)	<0.0001	7.51 (0.72)	<0.0001
Facility type (multilane)	-105.52 (14.76)	<0.0001	-70.56 (16.75)	<0.0001	-8.79* (17.02)	0.6057

Note: SE = standard error. Facility type: 1 if multilane, 0 if two-lane highway.

*Indicates not significant at 95% confidence.

predictors with a conditional quantile of an outcome variable without assuming any specific conditional distribution. As a result, it models the quantiles instead of the mean as done in standard linear regression (ordinary least squares [OLS]). Similarly, QR does not make any assumptions about data distribution like the standard regression, which makes it more robust to handle outliers and amenable to skewed distributions (17).

In this study, QR was used to estimate the 50th, 70th, and 85th percentiles of the upstream and downstream influence areas. Taking a comparable structure to the linear regression model, the QR model equation in the context of this study for the τ th quantile is:

$$Q_{\tau}(y_i) = \beta_0(\tau) + \beta_1(\tau)x_{i1} + \dots + \beta_p(\tau)x_{ip} + \varepsilon_i, \quad i = 1, 2, \dots, n \quad (1)$$

where $Q_{\tau}(y_i)$ is the τ th quantile of the influence area distribution, x_{ij} s are observed independent variables associated with observation i , $\beta_j(\tau)$ is the beta coefficient function of quantile level τ for variable j , and ε_i is a random error term with a mean equal to zero. $\beta_j(\tau)$ are estimated by solving the minimization problem as given in Equation 2:

$$\min_{\beta_0(\tau), \dots, \beta_p(\tau)} \sum_{i=1}^n \rho_{\tau}(y_i - \beta_0(\tau) - \sum_{j=1}^p x_{ij} \beta_j(\tau)) \quad (2)$$

$$\text{where } \rho_{\tau}(r) = \tau \max(r, 0) + (1 - \tau) \max(-r, 0) \quad (3)$$

The function $\rho_{\tau}(r)$ is referred to as the check loss that gives asymmetric weights to each of the individual error r for each data point, depending on the quantile and the sign of the error. For positive errors, the check function multiplies the error by τ , and by $(1 - \tau)$ if the error is

negative. Minimizing Equation 2 results in minimum median absolute deviation for the quantile model. For each quantile level τ , the solution to this minimization problem yields a distinct set of regression coefficients $\beta_0(\tau)$ and $\beta_j(\tau)$ (18). In this study, the “quantreg” package (19) in rStudio was used to estimate QR models for the intersection influence areas.

The parameter estimates for the signalized intersection upstream and downstream influence area models are presented in Table 6. For each quantile model, parameter estimates are provided, along with standard errors and the p -value that corresponds to the t -statistic used to evaluate whether each of these parameters was significantly different from zero. The results imply that the length of the upstream influence area at signalized intersections is directly related to the running speed on the upstream segment and the percentage of trucks (heavy vehicles), and a multilane highway has a shorter influence area than the two-lane highway (facility type).

For stop-control intersections, the models were developed only for the upstream influence area and the parameter estimates are presented in Table 7. Different variables were tested as regressors in the model such as AADT and heavy vehicle percentage. However, only running speed on the upstream segment was found statistically significant in the three models presented in Table 7. The probable reason is that roadways at the study sites, similar to most rural roadways, usually operate near free-flow conditions (well below capacity) and a low percentage of heavy vehicles was observed at the study sites. For each quantile (50th, 70th, and 85th) model, parameter estimates are provided, along with standard errors and the p -value that corresponds to the t -statistic used to evaluate whether each of these parameters was significantly different from zero. The results (summarized in Table 7)

Table 7. Linear Quantile Regression Model for Influence Area of Stop-Control Intersection

Parameters	$\tau = 0.50$		$\tau = 0.70$		$\tau = 0.85$	
	Estimate (SE)	p-value	Estimate (SE)	p-value	Estimate (SE)	p-value
Dependent variable: upstream influence area length (ft)						
Intercept	-387.79 (38.74)	<0.0001	-408.91 (47.17)	<0.0001	-507.80 (72.95)	<0.0001
Upstream running speed (mph)	21.47 (0.80)	<0.0001	23.90 (1.01)	<0.0001	27.80 (1.47)	<0.0001

Note: SE = standard error.

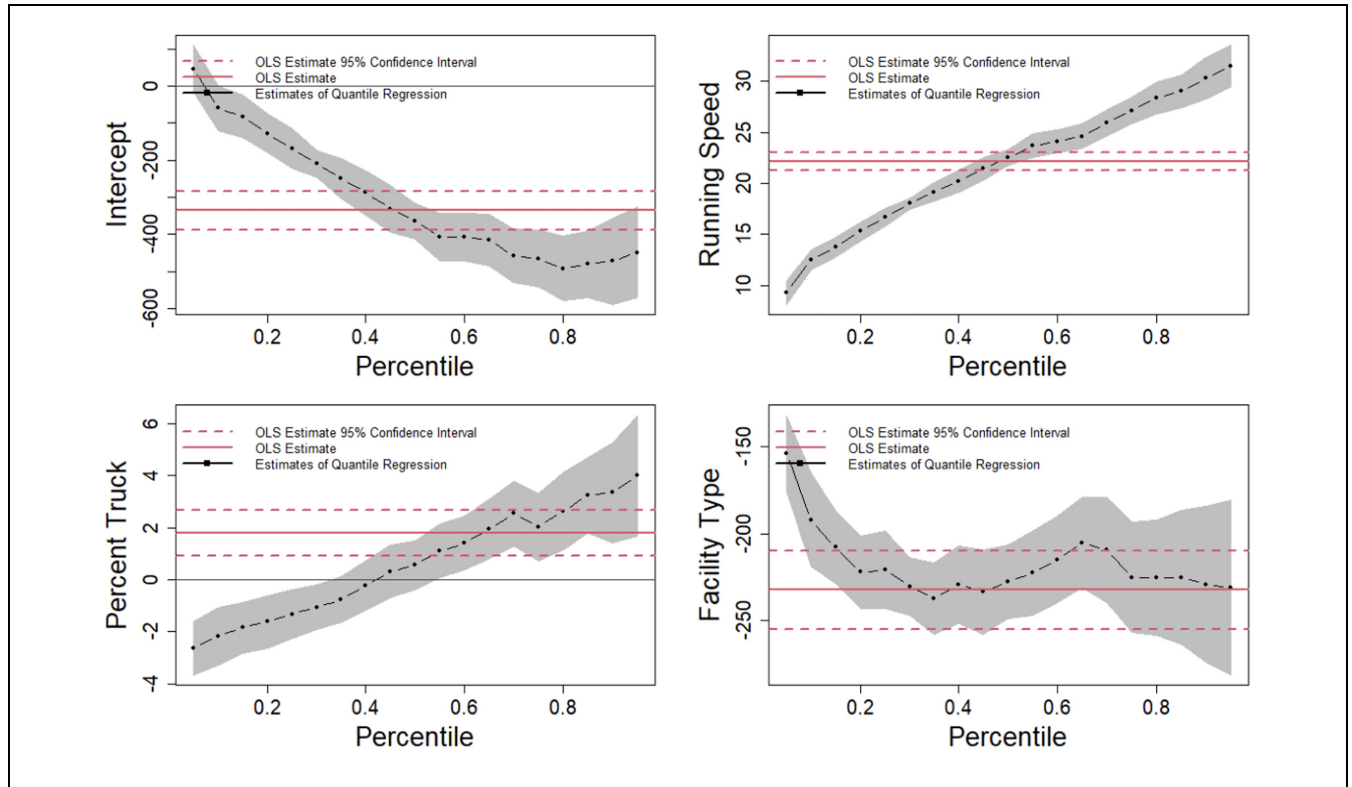


Figure 10. Comparison of parameter estimates: quantile versus ordinary least squares regression for upstream influence area at signalized intersections.

imply that the length of the stop-control intersection upstream influence area is directly related to the running speed on the upstream segment.

Figures 10–12 provide a graphical comparison of the parameter estimates for each quantile along with the same estimates for an OLS regression model of the mean influence area. When examining these plots, the OLS parameter estimates are reflected by a horizontal solid red line along with the associated 95% confidence intervals (CI) represented by dashed red lines. If the QR parameter estimates fall outside of the 95% CI boundary, it implies that the difference between the OLS parameter estimate and the QR estimate is statistically significant at the 95% confidence level. For instance, Figure 10

illustrates that the parameter estimates of the upstream running speed (top-right plot) are statistically significantly different from the parameter estimates of OLS for all percentiles except in the range of 45th–55th percentiles (lie within the boundaries of 95% CI of OLS parameter estimates). Similarly, the parameter estimates of the downstream influence area model at different quantiles are mostly located outside of the 95% confidence boundary of OLS parameter estimates, as shown in Figure 11, and therefore are statistically significantly different from the OLS estimates. Thus, this analysis suggests that QR is able to identify relationships in the data that would not be otherwise possible under the more typical OLS framework.

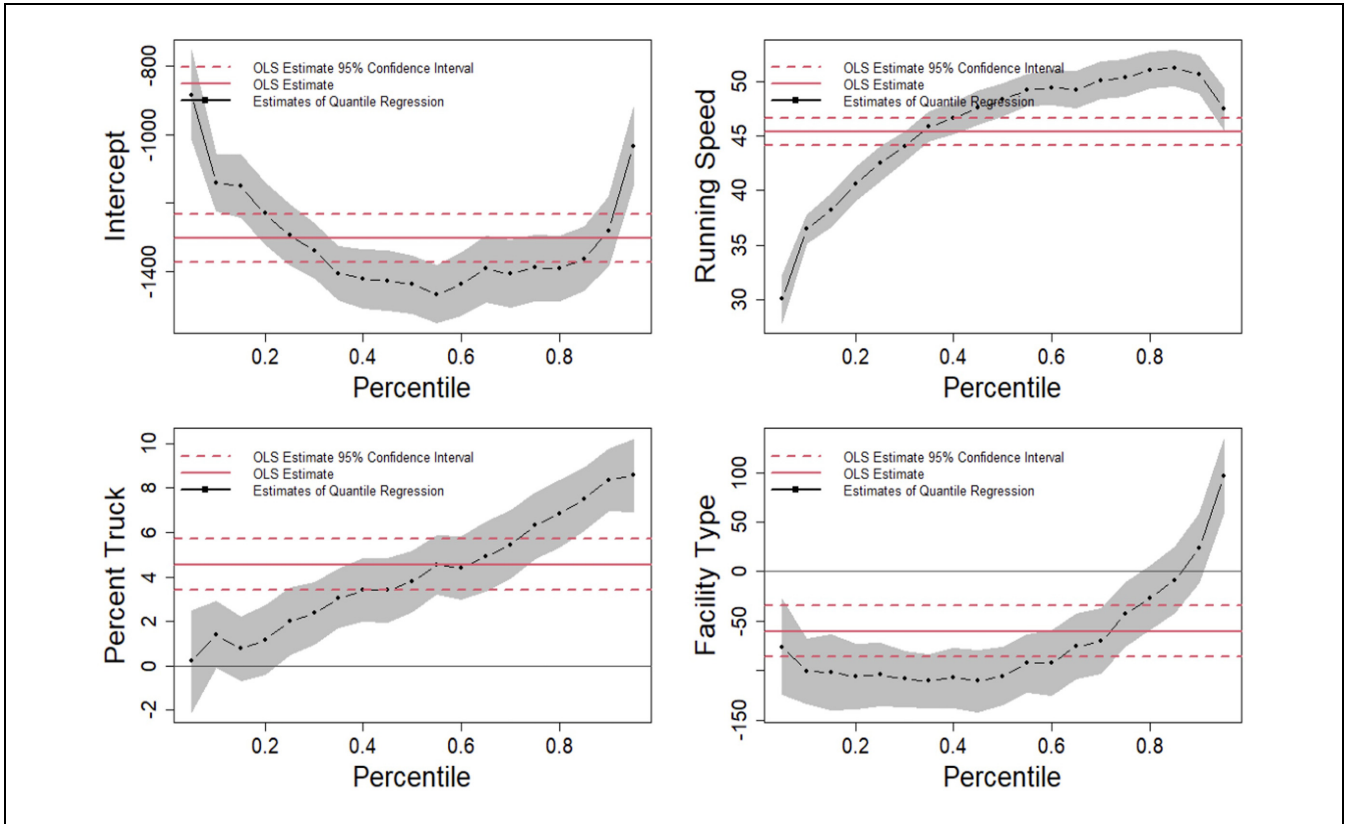


Figure 11. Comparison of parameter estimates: quantile versus ordinary least squares regression for downstream influence area at signalized intersections.

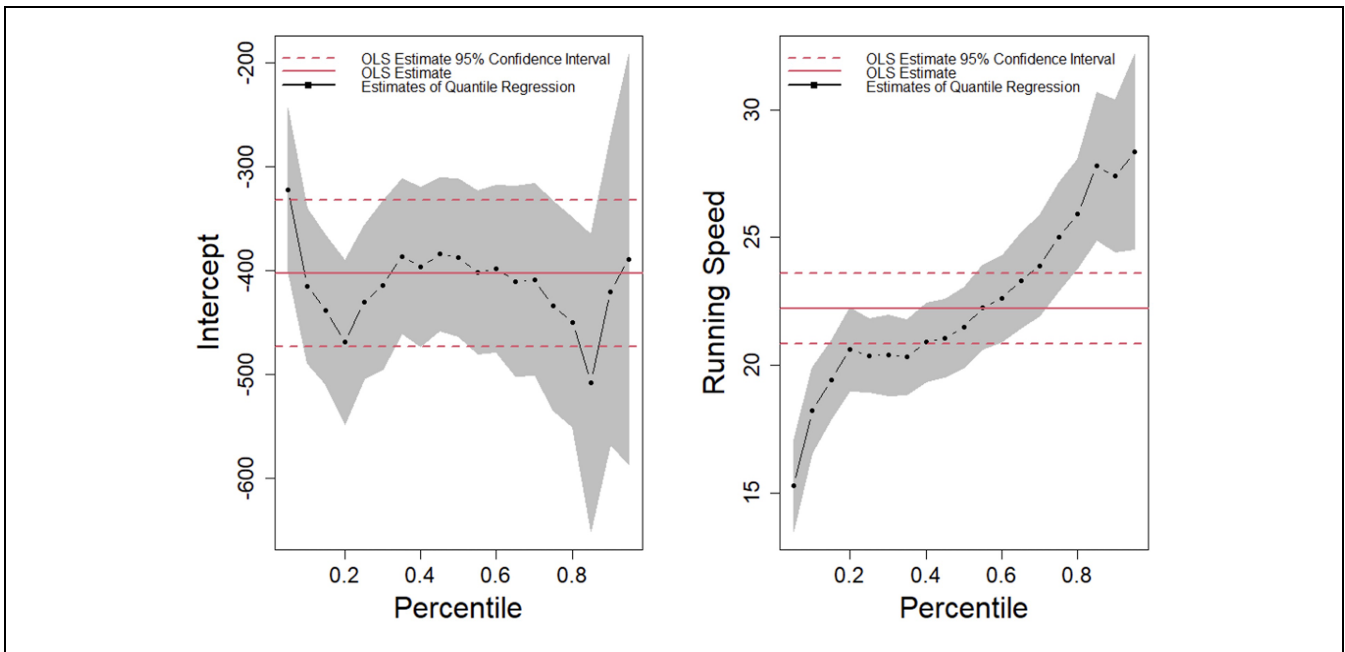


Figure 12. Comparison of parameter estimates: quantile versus ordinary least squares regression for upstream influence area at stop-control intersection.

Conclusions and Recommendations

The main objective of this study was to assess the influence of signalized and stop-control intersections on traffic performance along connecting roadway segments and delineate the intersection upstream and downstream influence areas. This is important to facilitate the operational analysis of highway facilities and corridors consisting of multiple segments and junctions. The study used empirical high-resolution trajectory data at four signalized intersection sites and seven stop-control intersection sites. A heuristic algorithm was developed to determine the upstream and downstream influence areas from processed trajectory data. The major findings of this research can be summarized below.

- The preliminary analysis using descriptive summaries revealed that the intersection downstream influence areas are considerably longer than the upstream influence areas for signalized intersections. It also indicates the association between the influence area length and the connecting segment running speed. Further, it was clear that the upstream influence areas for signalized intersections are longer than those for stop-control intersections even for comparable segment running speeds, possibly because of the presence of queues during the red signal phase.
- The average length of the upstream influence area at signalized intersections ranged from 547 ft to 1443 ft for the study sites with an average running speed ranging from 43 mph to 70 mph, respectively. Similarly, the average downstream influence area length at signalized intersections ranged from 650 ft to 1822.5 ft for study sites with average running speeds ranging from 42 mph and 67 mph, respectively. This indicates that deceleration rates upstream of the signalized intersections are greater in magnitude than the acceleration rates downstream of the signalized intersections.
- Similarly, the average length of the upstream influence area at stop-control intersections ranged from 517 ft to 904 ft for the study sites with an average running speed ranging from 45 mph to 59 mph, respectively. Although the downstream influence areas at stop-control intersections were not investigated in this research, they are expected to be similar to those at the signalized intersections, except for the possible effect of platoons released at the start of the green phase on acceleration rates.
- The analysis of influence area percentiles and speed reduction/difference is important in estimating the level of operational impacts because of the deceleration and acceleration taking place within the influence areas. It also showed the importance

of considering not only the magnitude of speed reduction/difference, but also the percentage of speed reduction/difference with reference to the average running speeds of the segment.

- The QR models developed for the estimation of the 50th, 70th, and 85th percentile influence areas at signalized intersections found segment running speed (upstream/downstream), percent heavy vehicles, and facility type (i.e., two-lane versus multilane highway) to have a significant effect in determining the percentile influence areas. However, in the case of stop-control intersections, only segment running speeds are found to be significant in the developed models for the estimation of the 50th, 70th, and 85th percentile influence areas. Facility type was not tested as an explanatory variable in the influence area models for the stop-control intersection as all the stop-control intersections are on two-lane highways.

The findings of this study contribute to the development of a performance analysis method for a rural highway corridor that consists of connected intersections. Influence areas for other types of intersections (e.g., roundabouts) are being developed as part of the same research effort. This would enable facility segmentation along rural highway corridors, which is critical for conducting facility-level operational analyses. This research used 11 study sites in Central Florida with all sites being in relatively flat terrain. It would be important to examine intersection influence areas in other regions to consider any possible effect of different driver populations (driver behavior) as well as different terrain to assess the effect of grades which are directly related to acceleration and deceleration distances. Apart from rural intersections, this study offers a basis to conduct similar investigations into intersection influence areas in urban environments.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Ahmed Al-Kaisy, Scott Washburn; data collection: Sajid Raza, Jorge Barrios; analysis and interpretation of results: Ahmed Al-Kaisy, Sajid Raza, Scott Washburn; draft manuscript preparation: Ahmed Al-Kaisy, Sajid Raza, Ana Tsui Moreno, Bastian Schroeder. Author. All authors reviewed the results and approved the final version of the manuscript.


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