Sight-Distance Requirements for Left-Turning Vehicles at Two-Way Stop-Controlled Intersections

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Abstract: The current highway geometric design guide provides a method for calculating intersection sight distance at two-way stop-controlled intersections by assuming that a departing driver on the minor road that would start from a resting position needs a fixed-time gap for departing the intersection regardless of the design speed or the grade on the major road. However, departing drivers may fail to perceive the speeds of the approaching vehicles on the major road in order to judge the available departure gap and decide whether or not to accept it. In this paper, a novel method is introduced to determine intersection sight distance requirements for two-way stop-controlled intersections based on actual drivers' behavior and vehicle capabilities. The method incorporates acceleration profiles for vehicles starting from rest, which were developed based on field data collected using global positioning system (GPS) data loggers that recorded the positions (latitudes, longitudes, and altitudes) and the instantaneous speeds of different vehicle types piloted by different drivers at 1 s intervals. Design tables and an application example are presented to help designers select the required intersection sight distance based on the design speed and the grade on the major road. **DOI: 10.1061/JTEPBS.0000018.** © *2016 American Society of Civil Engineers.*

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Introduction

Safety at nonsignalized intersections is a key concern for highway designers. According to the National Highway Traffic Safety Administration (NHTSA 2016), a total of 2,148 fatal collisions occurred in the United States at nonsignalized intersections from 2011 to 2013. At a two-way stop-controlled (TWSC) intersection the driver of a stopped vehicle on the minor road typically needs an unobstructed line of sight along the uncontrolled major road for safe departure. This unobstructed distance is the intersection's departure sight distance. The current geometric design guide provided by the AASHTO (2011) suggests a methodology for computing intersection sight distance for TWSC intersections. That methodology is based on prior research studies (Harwood et al. 1996, 2000) where the departing driver on the minor road is assumed to need a fixed time gap regardless of the speed on the major road. For a typical passenger car, a minimum (critical) gap of 7.5 seconds (s) was assumed for left-turn departure (Case B1), and a critical gap of 6.5 s was assumed for right-turn departure (Case B2) and crossing departure (Case B3). An adjustment of 0.5 s was to be added to the recommended critical gaps of left-turn and crossing departures for major roads that have more than two lanes. Another adjustment of 0.2 s (for left-turn departure) or 0.1 s (for crossing and right-turn departures) was to be added for each percent grade if the minor road has an upgrade that exceeds 3%. No adjustments were provided or recommended to account for grades on the major road.

There are some limitations related to the preceding method (AASHTO 2011). The method is based on the assumption that the departing driver would be able to anticipate the time needed for the nearest vehicle on the major road to reach the intersection (the time gap) and therefore would make a decision whether to accept that gap and depart the intersection or reject the gap and wait for another adequate gap. Since humans are unable to directly perceive time gaps, it is assumed that the departing driver would actually perceive the distance to the nearest approaching vehicle on the major road along with its speed and acceleration rate so that the departing driver would indirectly anticipate the gap available and make a decision whether or not to accept that gap. Prior studies show that humans may be capable of precisely perceiving distances, but they usually have inadequate abilities to perceive the speed and acceleration of in-depth moving objects (López-Moliner et al. 2003; Watamaniuk and Heinen 2003; Watamaniuk and Duchon 1992; Werkhoven et al. 1992; Gottsdanker 1956). This means that a departing driver on the minor road may be incapable of precisely perceiving the speed and acceleration of vehicles on the major road. Furthermore, for left-turn and right-turn departures the gap-acceptance concept is based on the assumption that the departing driver would also be able to anticipate the time and distance needed to accelerate to the same speed of the nearest approaching vehicle on the major road to avoid conflict. This assumption adds even more mental demand to the driver of the turning vehicle who should anticipate the distance to the nearest approaching vehicle, its speed and acceleration rate, and the time and/or distance needed to accelerate to the same speed of the approaching vehicle.

Due to the complexity of the preceding mental tasks, some drivers may fail to precisely perceive all those details and consequently select inadequate gaps for their departures, which may result in traffic collisions. Another issue in the gap-acceptance method is the lack of provision for any adjustments for the suggested gaps when the grade on the major road is steep. This is despite the fact that turning drivers would need more time and distance to accelerate on a steep upgrade along the major road.

The purpose of this study is two-fold. The first purpose is to introduce a new method for calculating the required intersection

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sight distance for left-turn departing vehicles, ISD_{LT}, at TWSC intersections. The new method explicitly accounts for the effects of major-road speed and grade on the required values of ISD_{LT} and provides a systematic generic framework for calculating ISD_{LT} at TWSC intersections. Other improvements include provision of terms that account for the perception-reaction time of the departing and approaching drivers, as well as the deceleration rate used by the approaching driver to reduce the speed if there is a potential conflict with the path of the turning vehicle. The second purpose of the paper is to develop a new acceleration profile for left-turn vehicles starting from rest at a typical TWSC intersection. The new profile is based on current vehicle characteristics and driver behavior patterns. The developed profile is used in conjunction with the new method to establish design tables for the required values of ISD_{LT} associated with different design speeds and grades on the major road at typical TWSC intersections.

The following section presents the new method for calculating ISD_{LT} at TWSC intersections. The next sections provide details on the data collection and preparation, followed by the development and validation of the statistical models used to establish the acceleration profile. Design guidelines are then presented, followed by discussion of the results and an application example. The last section provides concluding remarks and recommendations for future research.

Proposed Method

The geometry of a typical TWSC intersection is shown in Fig. 1. As noted, the departing (shaded) vehicle on the minor road is at an initial position (D1) at the start of its departure. For safe departure an adequate intersection sight distance for right-turning departure, ISD_{RT}, is needed to the left of the departing driver; another adequate intersection sight distance for a left-turn departure, ISD_{LT}, is also needed to the right of the departing driver. For a left-turn departure, the nearest approaching (nonshaded) vehicle on the major road is located at position A1 at a distance ISD_{LT} upstream of the intersection. The approaching vehicle on the major-road is assumed to be traveling towards the intersection at the design speed V.

According to the findings of prior research studies (AASHTO 2011; Harwood et al. 1996, 2000), an approaching driver on the major road is expected to reduce their speed by approximately 30% of the design speed by applying a comfortable deceleration rate, a_d, which is less than the suggested deceleration rate of $3.05\ m/s^2$ for stopping sight distance. Thus, the total distance needed by the departing vehicle to accelerate to 70% of the design speed on the major road is d_1, which is traveled during period t_1. That distance consists of the distance traveled during the turning maneuver, d_{11}, and the subsequent distance traveled along the major road to accelerate to 70% of its design speed, d_{12}. The distances d_{11} and d_{12} are traveled during time periods t_{11} and t_{12}, respectively. The sum of t_{11} and t_{12} is the total acceleration time t_1. At the end of t_1, the departing vehicle would have reached position D2 and the approaching vehicle would have reached position A2 at downstream distance d_2 from its initial position. As shown in Fig. 1, the minimum required ISD_{LT} is given by

$$ISD_{LT} = d_2 + L_h - d_{12} - d_T \qquad (1)$$

where ISD_{LT} = minimum required intersection sight distance for left-turn departure (m); d_2 = distance traveled by the approaching vehicle while the departing vehicle was turning and accelerating (m); L_h = distance corresponding to a safe time-headway that must be maintained between the departing and the approaching vehicles at the end of the maneuver (m); d_{12} = distance traveled by the

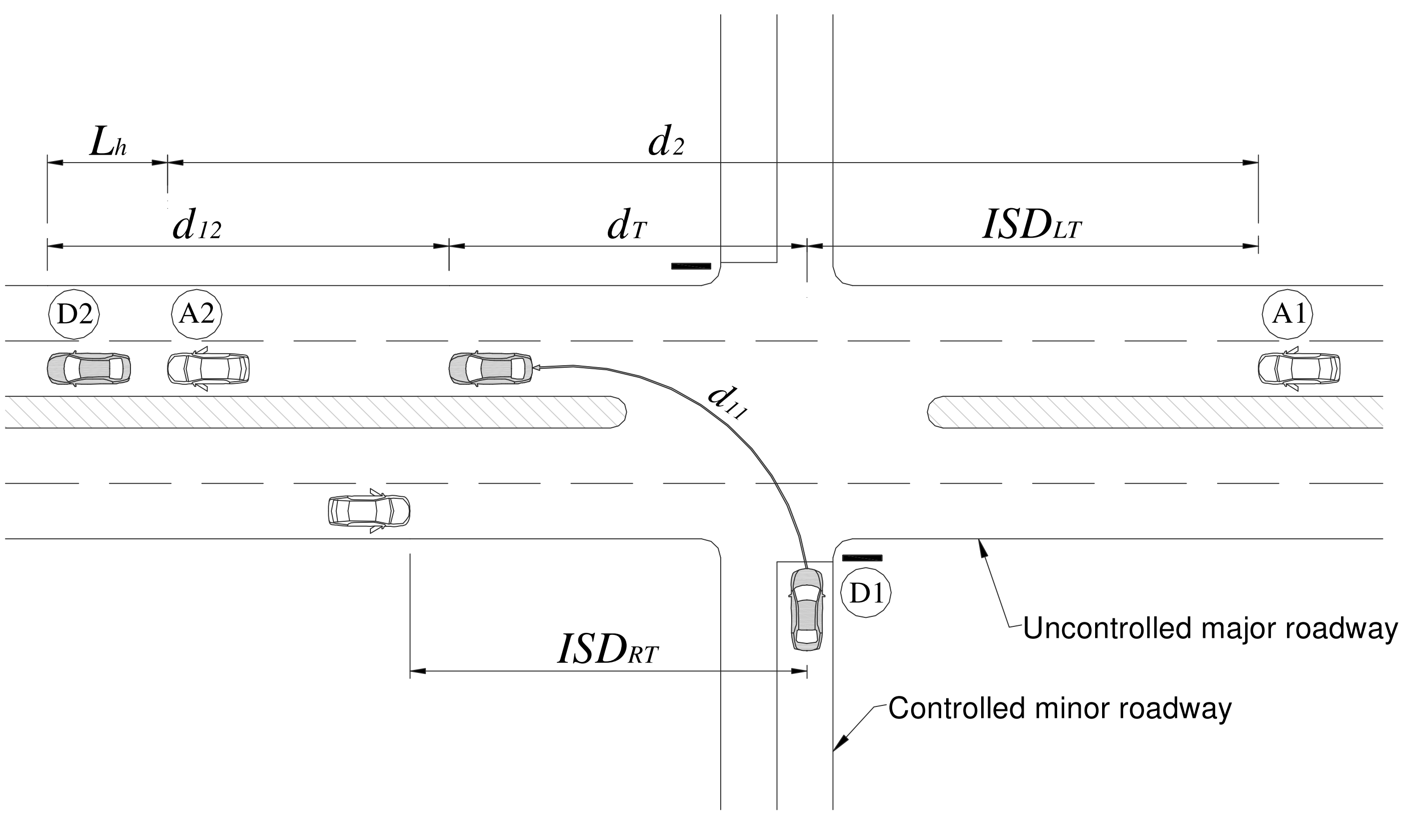

Fig. 1. Sight distance for a left-turn vehicle at a typical two-way stop-control intersection

departing vehicle after completing its turning maneuver to accelerate to 70% of the design speed on the major road (m); and d_T = distance traveled by the departing vehicle while turning, d_{11}, projected along the major road (m).

For simplicity and similar to the assumptions made in other studies (Harwood et al. 1996, 2000), the turning distance along the vehicle path, d_{11}, is assumed to be a circular arc with radius R and central angle 90°. For a passenger car, that radius is less than the typical design radii required by AASHTO (2011), which are usually designed for larger-design vehicles. Therefore, the turning distance of the departing vehicle, d_{11}, is given by

$$d_{11} = \frac{\pi R}{2} \tag{2}$$

The projected component of the turning distance along the major road is given by

$$d_T = R \tag{3}$$

The time needed by the departing vehicle to make its turn, t_{11}, and the speed at the end of the turn, v_{11}, are both related to the turning distance, d_{11}. To calculate these variables, the acceleration profile of the departing vehicle is needed. Since the departing vehicle is typically starting from rest, the assumption of a constant acceleration rate was found to be unrealistic due to the fact that the acceleration rate generally decreases as the speed increases (Perco et al. 2012; Rakha et al. 2004; Wang et al. 2004). Therefore, several models were introduced to establish the acceleration profile of a vehicle starting from rest. From among those models, the linear-decreasing model was selected by several researchers due to its simplicity and accuracy (Wang et al. 2004; Long 2000; Rao and Madugula 1986; Drew 1968). According to that model, the acceleration at any time is given by

$$a = dv/dt = \alpha - \beta v \pm G_1 g \tag{4}$$

where a = acceleration rate corresponding to a certain speed v (m/s^2); v = vehicle speed (m/s); α = acceleration rate at the start of acceleration (m/s^2); β = rate of change of acceleration with respect to speed (s^{-1}); G_1 = grade of the minor road (m/m); and g = gravity (approximately 9.81 m/s^2).

By integrating Eq. (4), the speed at any time, v, may be obtained as

$$v = [(\alpha \pm G_1 g)/\beta] - \{[(\alpha \pm G_1 g)/\beta] - v_0\}e^{-\beta t} \tag{5}$$

where t = time elapsed from the start of acceleration (s); and v_0 = initial speed of the vehicle (m/s). The distance traveled at any time, d, may be obtained by integrating Eq. (5), giving

$$d = [t(\alpha \pm G_1 g)/\beta] - \{[(\alpha \pm G_1 g)/\beta] - v_0\}[(1 - e^{-\beta t})/\beta] \tag{6}$$

By applying Eq. (6), the time needed for the departing vehicle to complete its turn, t_{11}, may be obtained given the turning distance, d_{11}, which is calculated from Eq. (2). Consequently, the speed of the departing vehicle at the end of its turn, v_{11}, may be calculated by applying Eq. (5) as follows:

$$v_{11} = [(\alpha \pm G_1 g)/\beta] - \{[(\alpha \pm G_1 g)/\beta - v_0]\}e^{-\beta t_{11}} \tag{7}$$

The time, t_{12}, needed for the departing vehicle to accelerate from speed v_{11} (at the end of its turning maneuver) to 70% of the design speed on the major road may be calculated by rearranging Eq. (5) and substituting the initial speed, v_o, with v_{11} [as calculated from Eq. (7)], and the final speed, v, with 0.194 V (where V is the design speed on the major road in km/h). Thus

$$t_{12} = -\ln\{[(\alpha \pm G_2 g)/\beta - 0.194\ V]/[(\alpha \pm G_2 g)/\beta - v_{11}]\}/\beta \tag{8}$$

where t_{12} = time needed for the departing vehicle to accelerate from speed v_{11} to 70% of the design speed on the major road (s); G_2 = grade of the major road (m/m); and V = design speed on the major road (km/h).

The total time, t_1, needed for the departing vehicle to accelerate from rest to 70% of the design speed on the major road is the sum of the time needed to complete the turning maneuver, t_{11} [given by Eq. (6)], and the time needed to accelerate to 70% of the major-road design speed, t_{12} [given by Eq. (8)].

The distance needed for the departing vehicle to accelerate to 70% of the design speed on the major road is obtained by using Eq. (6) after substituting the term t with t_{12} [as given by Eq. (8)] and the terms G_1 and v_o with G_2 and v_{11}, respectively

$$d_{12} = [t_{12}(\alpha \pm G_2 g)/\beta] - \{[(\alpha \pm G_2 g)/\beta] - v_{11}\}[(1 - e^{-\beta t_{12}})/\beta] \tag{9}$$

The distance, d_2, traveled by the approaching major-road vehicle while the departing vehicle is turning and accelerating includes the following four different segments:

1. The first segment is the distance traveled by the approaching vehicle at the design speed, V, while the driver of the departing vehicle, on the minor road, is perceiving the situation, making a decision to start departure, and making the necessary actions to start the departure (e.g., shifting the gear and moving the foot to the accelerator pedal);
2. The second segment is the distance traveled by the approaching vehicle at the design speed, V, while its driver is realizing that the vehicle on the minor road has started its departure. This segment also includes the distance traveled by the approaching vehicle while its driver is activating the brakes to start reducing the speed by up to 30%;
3. The third segment is the distance needed by the approaching vehicle to reduce its speed by 30% at a deceleration rate, a_d; and
4. The fourth segment is the distance traveled by the approaching vehicle at 70% of the design speed while the driver of the departing vehicle is accelerating to that same speed.

Therefore, the distance, d_2, may be expressed as

$$d_2 = 0.278\ V(t_{PR1} + t_{PR2}) + \left(\frac{0.019676V^2}{a_d \pm gG_2}\right) + 0.194\ V\left[t_1 - t_{PR2} - \left(\frac{0.083}{a_d \pm gG_2}\right)\right] \tag{10}$$

where t_{PR1} = perception-reaction time of the driver of the departing vehicle on the minor road (s); t_{PR2} = perception-reaction time of the driver of the approaching vehicle on the major road (s); a_d = deceleration rate used by the driver of the approaching vehicle to reduce the speed by 30% (m/s^2); and t_1 = overall time needed for the departing vehicle to accelerate from rest to 70% of the design speed on the major road, which is the sum of the times t_{11} [of Eq. (6)] and t_{12} [of Eq. (8)].

Finally, the term L_h in Eq. (1) is the distance corresponding to a safe time-headway that must be maintained between the departing and the approaching vehicles at the end of the maneuver when both vehicles are traveling at 70% of the design speed on the major road. This term is given by

$$L_h = 0.194\ V t_h \tag{11}$$

where t_h = minimum safe time-headway that must be maintained between the departing and approaching vehicles at the end of the maneuver (s). This time is assumed to be 2 s by AASHTO (2011) and the Highway Capacity Manual (HCM) published by the Transportation Research Board (TRB 2010). To summarize, the minimum ISD_{LT} is given by Eq. (1) where d_2, L_h, d_{12}, and d_T are given by Eqs. (10), (11), (9), and (3), respectively.

Different values for the coefficients α and β [in Eqs. (4)–(9)] were previously proposed for a typical passenger car by assuming linear-decreasing acceleration models. Wang et al. (2004) studied acceleration behavior of vehicles starting from rest at all-way stop-controlled intersections by collecting data from over 100 private vehicles in the Atlanta urban area that were equipped with global positioning system (GPS) data logger devices. One model was developed for straight departure with values of α and β found to be 1.883 m/s^2 and 0.0756 s^{-1}, respectively. Another model was developed for turning departure with values of α and β found to be 1.646 m/s^2 and 0.0612 s^{-1}, respectively. Long (2000) conducted a synthesis review to find appropriate design values for α and β, and concluded that the appropriate values of those parameters that appear to be consistent with most observations of average motorist behavior were 2.00 m/s^2 and 0.12 s^{-1}, respectively. Bonneson (1992) conducted a research study to model acceleration behavior of drivers starting from rest at signalized intersections. The values of α and β were found to be 2.02 m/s^2 and 0.1326 s^{-1}, respectively.

The aforementioned values of the coefficients of α and β are based on actual drivers' behavior and vehicle capabilities, which are different from the maximum mechanical capabilities suggested by vehicle manufacturers. This is due to the fact that most drivers do not apply the maximum acceleration capabilities of their vehicles unless in emergency situations (Perco et al. 2012; Wang et al. 2004; Long 2000). Additionally, all of those aforementioned models are based on experiments conducted more than ten years ago. The authors of this paper are not aware of any newer models that are based on the linear-decreasing acceleration model. Given the ongoing changes in vehicle design and driver characteristics, statistical models are developed in the following section to provide more realistic recent values for coefficients α and β that reflect the characteristics of current modern vehicles and drivers. As explained in the next section, the statistical models are based on actual experimental data collected from the field.

Data Collection

GPS Data Logger

As previously discussed, realistic values are needed for coefficients α and β that were used to establish an acceleration profile for left-turn vehicles starting from rest based on the characteristics of current modern vehicles and drivers. Those values are also needed to calculate the distance, d_1, traveled by the departing vehicle while making its turn and accelerating to 70% of the design speed on the major road. As discussed earlier, drivers do not usually apply the maximum acceleration capabilities of their vehicles unless in emergency situations, and therefore they usually select the acceleration parameters, α and β, that are less than the boundary values provided by the mechanical characteristics of their vehicles. Based on this information, GPS data logger devices were used to collect data about acceleration profiles selected by different drivers when making left-turn departures from stop-control minor roads into uncontrolled major roads. Based on the collected data, statistical models were developed to provide realistic estimates of the coefficients α and β and to establish the acceleration profile for left-turn vehicles starting from rest. The devices recorded the latitudes, longitudes, altitudes, and the instantaneous speeds of the equipped vehicles at 1-s intervals. The records collected by the devices were extracted to a personal computer in the form of spreadsheets that show all the records collected where each record is shown in a separate row in the spreadsheet representing the data collected during a certain 1-s interval.

Table 1 shows a sample of a spreadsheet extracted from the actual data collected for one left-turning maneuver. The records were also extracted to maps in the form of continuous tracks of the equipped vehicles shown on those maps. The exact locations of left-turn departures from stop positions at TWSC intersections were identified on the maps and the corresponding records were extracted from the spreadsheets for analysis. The date and time stamps associated with each record were used to link the maps with the spreadsheets. As an example, according to the data shown in Table 1 the subject driver started turning to the left from rest (zero speed) at 11:35:06 on June 6, 2015 and reached a speed of 63.4 km/h at 11:35:24 on the same day. According to the table, that subject driver needed 18 s to accelerate from a speed of zero

Table 1. Sample Spreadsheet Created by the GPS Data Logger Device

Index	Track number	Local date	Local time	Latitude	N/S	Longitude	E/W	Altitude	Speed (km/h)
1,138	1	6/6/2015	11:35:06	24.40175	N	54.57946	E	8.564209	0.0
1,139	1	6/6/2015	11:35:07	24.40175	N	54.57946	E	7.946899	0.1
1,140	1	6/6/2015	11:35:08	24.40175	N	54.57946	E	7.981323	0.1
1,141	1	6/6/2015	11:35:09	24.40175	N	54.57946	E	8.010742	0.6
1,142	1	6/6/2015	11:35:10	24.40175	N	54.57946	E	8.042236	4.2
1,143	1	6/6/2015	11:35:11	24.40177	N	54.57945	E	7.413208	12.1
1,144	1	6/6/2015	11:35:12	24.4018	N	54.57942	E	7.391113	17.2
1,145	1	6/6/2015	11:35:13	24.40179	N	54.57937	E	8.328125	18.9
1,146	1	6/6/2015	11:35:14	24.40176	N	54.57932	E	9.501465	27.8
1,147	1	6/6/2015	11:35:15	24.40174	N	54.57923	E	9.990479	35.0
1,148	1	6/6/2015	11:35:16	24.40172	N	54.57913	E	10.38159	40.8
1,149	1	6/6/2015	11:35:17	24.40169	N	54.57901	E	11.08057	46.2
1,150	1	6/6/2015	11:35:18	24.40167	N	54.57887	E	11.41504	51.1
1,151	1	6/6/2015	11:35:19	24.40164	N	54.57873	E	11.83789	54.9
1,152	1	6/6/2015	11:35:20	24.40161	N	54.57857	E	11.97437	57.8
1,153	1	6/6/2015	11:35:21	24.40158	N	54.57841	E	11.79663	59.8
1,154	1	6/6/2015	11:35:22	24.40155	N	54.57824	E	11.59155	61.7
1,155	1	6/6/2015	11:35:23	24.40151	N	54.57807	E	11.37231	63.3
1,156	1	6/6/2015	11:35:24	24.40148	N	54.57789	E	11.16333	63.4

to a speed of 63.4 km/h, where the initial and final positions (latitude, longitude, and altitude) are as shown on the first and last rows of the table, respectively. As reported by the manufacturer of the GPS data logger devices used in this research (Holux M-1000C), the precision level in measuring the speed is 0.1 m/s (Holux Technology 2016).

Given that the total number of records for one departure is n, the acceleration rate at any second (i) is estimated as the average of the acceleration rates half a second earlier ($i - 0.5$) and half a second later ($i + 0.5$) as follows:

$$a_i = (a_{i+0.5} + a_{i-0.5})/2 \tag{12}$$

where a_i = estimated acceleration rate at the ith second; $a_{i+0.5}$ = acceleration rate at the $(i + 0.5)$th second, and $a_{i-0.5}$ = acceleration rate at the $(i - 0.5)$th second.

Since the records are collected every second, the acceleration rate at any time interval i is calculated as the difference between the speeds one second before and one second after time interval i, divided by the time difference (2 s). Thus, the acceleration rate is given by

$$a_i = (v_{i+1} - v_{i-1})/2 \tag{13}$$

where v_{i+1} = instantaneous speed (m/s) at the $(i + 1)^{\text{th}}$ second; and v_{i-1} = instantaneous speed (m/s) at the $(i - 1)^{\text{th}}$ second.

Acceleration Data

The statistical models used to estimate the coefficients α and β were developed based on data collected from April 2015 to September 2015 from 32 different participating drivers, including 17 male drivers and 15 female drivers. The age of the drivers ranged from 19 to 77 years with a mean age of 38.1 years (standard deviation 18.7 years) and a median age of 32 years. The participating drivers included 13 drivers in the younger age group (below 25), 8 drivers in the middle age group (25–44), 7 drivers in the older age group (45–65), and 4 drivers in the senior age group (above 65). There were 11 drivers from Toronto metropolitan area in Canada and 21 drivers from the Abu Dhabi metropolitan area in the United Arab Emirates. The highway design guidelines and traffic rules in both countries are comparable to those in the United States.

A GPS data logger device was installed in the private vehicle of every participating driver. The drivers were asked to drive their vehicles for their normal daily routine activities for three to four days before returning the device to the researchers to download the data for analysis. All drivers signed consent forms acknowledging and accepting the fact that the devices would collect data related to their driving activities and position details, with anonymity assured to all drivers. Since the drivers were asked to drive their own vehicles, the number of vehicles used in the experiment was also 32 vehicles, including 19 passenger cars, 7 sports-utility vehicles, 5 minivans, and 1 pickup truck. The age of the vehicles varied from one year (for the newest vehicle) to 16 years (for the oldest vehicle), with a mean age of all vehicles of 5.7 years (with a standard deviation of 4.0 years) and a median age of 4.0 years. Based on the data collected from respective vehicle manufacturers, the net horsepower (hp) of vehicle engines ranged from 106 hp at 6,000 revolutions per minute (rpm) (for a 2010 Toyota Yaris) to 400 hp at 6,000 rpm (for a 2012 Nissan Patrol). The mean horsepower of all vehicles was 207.9 hp (with a standard deviation 69.4 hp) and the median was 193.5 hp. All the major roads that the drivers were turning into had low to moderate traffic volumes with annual average daily traffic (AADT) volume of less than 50,000 vehicles per day. The AADT limit selected to define roads with low to moderate traffic volumes is based on the guidelines presented by the United States Federal Highway Administration (FHWA 2004).

After excluding *rolling* departures where drivers did not fully stop at intersections, there were 913 left-turn departures (acceleration profiles) that were used for analysis. All acceleration profiles selected for analysis were for left-turn departures where minor and major roads have moderate grades with grades less than 2%. Furthermore, by inspecting the maps of all the intersections associated with the acceleration profiles selected for analysis, they all had adequate intersection sight distance so that drivers would accelerate normally with no effect on their acceleration behavior by any limitation of the available intersection sight distance.

The profiles selected included 578 profiles for left-turn departures into two-lane major roads (with one lane in each direction), and 335 profiles for left-turn departures into four-lane major roads (with two lanes in each direction). There were 11,926 records (rows) associated with all the departure profiles. There were 760 profiles (with 9,485 records) used for model development, and the remaining 153 profiles (with 2,441 records) were reserved for model validation.

Acceleration Profile Models

Model Development and Validation

Since the dataset comprise several subsets where each subset includes observations of repeated departures by the same driver and the same vehicle, the linear mixed model was used for analyzing the data (Jiang 2007). Linear mixed models are particularly useful for analyzing correlated data so that both fixed and random effects are allowed to be included in the models. The fixed effects are those similar to the ones found in linear regression models, and the random effects are those related to the correlation due to repeated observations. The linear mixed model may be expressed as

$$y = X\beta + Z\alpha + \varepsilon \tag{14}$$

where y = vector of observations; X = matrix of known covariates; β = vector of unknown regression coefficients (for the fixed effects); Z = known matrix; α = vector of random effects; and ε = vector of errors; it should be noted that both α and ε are unobservable. The basic assumptions associated with the linear mixed model are that the random effects, α, and the errors, ε, are uncorrelated with mean values of zero and finite variances (Jiang 2007). The Bayesian information criterion (BIC) is used to compare different linear mixed models so that the model that best fits the data is selected. The BIC is estimated as follows (Schwarz 1978):

$$BIC = -2. \ln \hat{L} + k. \ln(n) \tag{15}$$

$$\hat{L} = p(x|\hat{\theta}, M) \tag{16}$$

where $\hat{L}$ = maximized value of the likelihood function of the model M; θ = parameter values that maximize the likelihood function; x = the observed data; n = number of data points in x (the number of observations); and k = number of free parameters to be estimated. The absolute BIC value, as computed by Eq. (14), has no interpretation. Instead, the BIC values are used to compare different candidate models together where the model with the lowest BIC value indicates better fit for the given data.

The *SPSS* statistical software (IBM 2016) was used for estimating the linear mixed model. Initially, a single model was attempted for each of the following two cases:

1. Case 1: left-turn departures into two-lane major roads; and
2. Case 2: left-turn departures into four-lane major roads.

The BIC values for the two models were found to be 7,737.915 and 8,555.669, respectively. Close inspection of the collected data revealed that the acceleration rate actually increases at the beginning of the departure while making the left-turn maneuver, and starts to decrease afterward while accelerating along the major road. This finding is consistent with that of previous studies that showed that the assumption of maximum acceleration at the start of the departure [as suggested by the linear-decreasing acceleration model shown in Eq. (4)] is unrealistic (Bham and Benekohal 2002; Pitcher 1989; Akcelik and Biggs 1987; Glauz et al. 1980). Therefore, the dataset related to each of the two cases was divided into two subsets. The first subset includes records related to an initial period when the departing drivers were turning, and the second subset includes the remaining records when the drivers were accelerating along the major roads. Based on that, the following four linear mixed models were then estimated:

1. The first model is for the initial turning segment into a two-lane major road;
2. The second model is for the subsequent segment along a two-lane major road;
3. The third model is for the initial turning segment into a four-lane major road; and
4. The fourth model is for the subsequent segment along a four-lane major road.

In each of the previously mentioned models, the dependent variable was the acceleration (a) in m/s^2 and the fixed effects were:

1. The speed (v) in m/s;
2. Driver age (*age*) in years;
3. Driver's gender (*gender*), which is a binary variable (*1* for male or *0* for female);
4. Location (*location*), which is a binary variable (*1* for Toronto or *0* for Abu Dhabi);
5. Vehicle age (*Veh_Age*) in years; and
6. Vehicle horsepower (*Veh_HP*) in horsepower.

It was found that at the 95% confidence level, only the speed (v) was found to be significant for all the four models. Additionally, the vehicle horsepower (*Veh_HP*) was found to be significant in the second model only. Based on this information, the insignificant variables were removed from the models in a stepwise fashion and the final models are shown in Table 2, which shows both the fixed and random effects. The BIC values for the final four models shown in Table 2 are 736.429, 666.875, 656.124, and 722.886, respectively. Note that the random effects (due to the correlated observations by the same drivers) are small but statistically significant in the four models.

For model validation 153 acceleration profiles (with 2,441 records) were used. They included 98 profiles (with 1,514 records) for left-turns into two-lane major roads and 55 profiles (with 927 records) for left-turns into four-lane major roads. The validation results showed that the values of the mean squared errors were insignificant for all four models with values of 0.118, 0.114, 0.049, and 0.247, respectively. Furthermore, the root mean squared errors for all models were small with values close to the sum of the random effects and the errors associated with the models. This indicates that the developed models were stable and robust when validated with data not used during calibration.

Comparison with Other Acceleration Profile Models

By combining the fixed and random effects at 95% confidence level, a comparison is provided in Table 3 between the values of the coefficients α and β of the developed models and those presented in selected research studies. As demonstrated in Table 3, the range of the values for the coefficient α during the initial turning segments is 1.0127–1.2899 (for turning into a two-lane major road) or 0.5775–0.8861 (for turning into a four-lane major road). These values are typically smaller than the values suggested in previous research studies (Wang et al. 2004; Long 2000; Bonneson 1992). However, the range of the values for the coefficient α during

Table 2. Final Models (Including Both Fixed and Random Effects)

Parameter	Estimate	Standard error	df	*t*-stat	Wald *Z*	Sigma	95% confidence interval	
							Lower bound	Upper bound
Initial turning into a two-lane major road								
Intercept	1.1513	0.0192	203.080	59.986	59.985	0.000	1.1134	1.1891
v	0.1608	0.0133	53.818	12.083	12.083	0.000	0.1341	0.1874
Residual variance[a]	0.0865	0.0032	—	—	26.922	0.000	0.0804	0.0930
Driver variance[a]	0.0050	0.0011	—	—	4.635	0.000	0.0033	0.0077
Subsequent turning into a two-lane major road								
Intercept	2.2526	0.0340	30.242	66.281	66.280	0.000	2.1833	2.3220
v	−0.0712	0.0009	4327.488	−82.455	82.503	0.000	−0.0729	−0.0695
Veh_HP	0.0004	0.0002	22.231	2.272	0.227	0.033	<0.0001	0.0008
Residual variance[a]	0.0492	0.0011	—	—	46.382	0.000	0.0472	0.0513
Driver variance[a]	0.0071	0.0014	—	—	5.138	0.000	0.0048	0.0097
Initial turning into a four-lane major road								
Intercept	0.7318	0.0157	1118	46.519	46.520	0.000	0.7009	0.7626
v	0.3484	0.0049	1118	70.507	70.51	0.000	0.3387	0.3581
Residual variance[a]	0.1026	0.0043	—	—	23.643	0.000	0.0944	0.1114
Driver variance[a]	0.0062	0.0013	—	—	4.968	0.000	0.0039	0.0083
Subsequent turning into a four-lane major road								
Intercept	2.5243	0.0265	2535.987	95.347	95.347	0.000	2.4724	2.5762
v	−0.1013	0.0023	321.916	−44.048	44.047	0.000	−0.1058	−0.0968
Residual variance[a]	0.2044	0.0086	—	—	23.781	0.000	0.1880	0.2217
Driver variance[a]	0.0097	0.0020	—	—	4.943	0.000	0.0061	0.0115

[a]For covariance parameters (for random effects).

Table 3. Comparison between the Developed and Exiting Acceleration Profiles

Model	Profile type	Departure type	α (m/s^2)	β (s^{-1})
Proposed two-lane	Two stage	Turning	1.0127–1.2899[a]	−0.1608
Two-lane	Two stage	Subsequent	2.1674–2.4977[a, b]	0.0712
Four-lane	Two stage	Turning	0.5775–0.8861[a]	−0.3484
Four-lane	Two stage	Subsequent	2.3313–2.7173[a]	0.1013
Wang et al. (2004)	One stage	Straight	1.8830	0.0756
Wang et al. (2004)	One stage	Turning	1.6460	0.0612
Long (2000)	One stage	Straight/turning	2.0000	0.1200
Bonneson (1992)	One stage	Straight/turning	2.0200	0.1326

[a]By combining the fixed and random effects at 95% confidence level.
[b]Assuming engine horsepower of 200 hp.

subsequent segments is typically larger than those suggested in those other research studies. On the other hand, the proposed values of β during the subsequent acceleration segment are comparable to those suggested by Wang et al. (2004) and are smaller than those suggested by Long (2000) and Bonneson (1992). The negative values of the coefficient β of the proposed models during the turning segments indicate that the acceleration rate does in fact increase during those segments, which is more realistic as was previously discussed.

The differences between the values of α and β given by the proposed models and those suggested by other studies may be due to the fact that those other studies assumed one-stage acceleration as compared to the two-stage acceleration used in the proposed models. Overall, the average values of the acceleration rate suggested by the proposed models over the two stages are within the range suggested by other researchers.

Design Guidelines

The design values of ISD_{LT} were calculated for different speeds and grades of the major road. Those values are based on the models presented in this paper. To calculate those values, the following assumptions are made (AASTO 2011; TRB 2010; Wang et al. 2004; Harwood et al. 2000, 1996; Long 2000; Rao and Madugula 1986; Drew 1968):

1. The setback distance between the front bumper of the departing vehicle and the edge of the traffic lane on the major road is 3.05 m;
2. The lane width is 3.6 m;
3. The perception-reaction time of the departing driver on the minor road, t_{PR1}, is 2.0 s;
4. The perception-reaction time of the approaching driver on the major road, t_{PR2}, is 2.5 s;
5. The minimum time-headway that must be maintained between the departing and approaching vehicles at the end of the maneuver, t_h, is 2.0 s; and
6. The effect of the major-road grade is as per the linear-decreasing acceleration model presented in Eq. (4).

In addition to the previously defined assumptions, a reasonable value was needed for the average deceleration rate, a_d, used by the driver on the major road to reduce the speed by 30%. A value of 1.50 m/s^2 is suggested by the AASHTO (2011). However, other research studies (Harwood et al. 1996; 2000) suggest a moderate value of 0.68 m/s^2. More recent research studies found that drivers are usually willing to apply a maximum deceleration rate of 2.6 m/s^2 in normal (not emergency) situations (Cunto and Saccomanno 2009, 2008). Based on these findings, the average value of 1.50 m/s^2 suggested by AASHTO (2011) was selected in this study for establishing the ISD_{LT} guidelines.

The design values of ISD_{LT}, which must be provided along the major road upstream of a typical TWSC intersection, are presented in Tables 4 and 5 for the cases of left-turn departures into two-lane and four-lane major roads, respectively. The values are calculated for different design speeds and grades on the major road by combining the fixed and random effects at 95% confidence level with assuming typical engine horsepower of 200 hp for the second model presented in Table 2 (subsequent acceleration segment while turning into a two-lane major road). Due to the small coefficient associated with the engine horsepower, changing the horsepower by ±50% will change the suggested values for ISD_{LT} by less than 2%. In addition to the suggested ISD_{LT} values, the following values are also presented in Tables 4 and 5:

1. The time, t_1, and distance, d_1, needed for the turning vehicle to accelerate to 70% of the design speed on the major road;
2. The distance, d_2, traversed by the approaching vehicle during the time when the turning vehicle is turning and accelerating to 70% of the design speed on the major road; and
3. The values of ISD_{LT} suggested by AASHTO (2011), rounded up to the nearest 5-m increments.

For moderate grades (up to 4%) and small design speeds (less than 60 km/h) on four-lane major roads where the turning radii for the intersections are large, turning vehicles typically accelerate to 70% of the major-road design speeds during the turning maneuver itself. Therefore, the turning vehicles do not need additional distance to accelerate to the target speed.

Discussion

Tables 4 and 5 indicate that the required values of ISD_{LT} based on the developed models are generally larger than those suggested by the current design guide (AASHTO 2011). The differences between the proposed values and AASHTO values are larger for large design speeds, even on downgrades. The AASHTO guide clearly underestimates the distance needed for the turning vehicles to accelerate along major roads with high design speeds, and therefore the ISD_{LT} values suggested by AASHTO (2011) may not allow departing drivers to accelerate to 70% of the design speed on the major road without conflicting with the paths of approaching vehicles.

Since the AASHTO guide does not provide any adjustment for ISD_{LT} if the major road has a steep grade, it underestimates the distance needed for the turning vehicles to accelerate on steep grades, and in turn it underestimates the required sight distance for this condition. This is due to the fact that the departing vehicles would theoretically experience substantial gravitational grade resistance on steep upgrades that would reduce the net power available to accelerate those vehicles.

Table 4. Design Values for Intersection Sight Distance for Vehicles Turning into a Two-Lane Major Road

Design speed on major road (km/h)	Major road grade (%)	t_1 (s)	d_1 (m)	d_2 (m)	L_h (m)	ISD_{LT} (m)	Rounded ISD_{LT}(m)	AASHTO ISD_{LT}[a] (m)
40	0	5.2	18.0	91.3	15.6	93.6	95	85
50		6.2	27.5	131.1	19.4	127.8	130	105
60		7.5	40.8	179.6	23.3	167.0	170	130
70		8.8	58.0	237.2	27.2	211.3	215	150
80		10.3	79.9	305.0	31.1	261.0	265	170
90		12.0	107.8	384.4	35.0	316.4	320	190
40	2	5.9	22.8	100.3	15.6	97.9	100	85
50		7.2	34.1	145.4	19.4	135.6	140	105
60		8.6	49.2	200.1	23.3	179.0	180	130
70		10.2	69.2	265.4	27.2	228.3	230	150
80		12.0	95.0	343.0	31.1	283.9	285	170
90		14.0	128.6	435.0	35.0	346.1	350	190
40	4	7.0	26.3	112.9	15.6	107.0	110	85
50		8.5	39.2	164.4	19.4	149.4	150	105
60		10.1	56.9	227.2	23.3	198.4	200	130
70		12.0	80.6	302.9	27.2	254.4	255	150
80		14.2	112.1	394.0	31.1	317.8	320	170
90		16.7	154.4	503.9	35.0	389.4	390	190
40	6	8.6	30.7	130.9	15.6	120.6	125	85
50		10.3	45.9	191.3	19.4	169.7	170	105
60		12.3	67.1	265.6	23.3	226.6	230	130
70		14.6	96.3	356.4	27.2	292.1	295	150
80		17.3	136.7	467.5	31.1	366.8	370	170
90		20.8	193.8	605.7	35.0	451.7	455	190
40	−2	4.5	17.9	83.8	15.6	86.3	90	85
50		5.5	26.8	120.5	19.4	117.9	120	105
60		6.6	38.6	164.4	23.3	153.9	155	130
70		7.8	53.7	216.1	27.2	194.4	195	150
80		9.1	72.8	276.6	31.1	239.7	240	170
90		10.6	96.6	346.8	35.0	290.0	290	190
40	−4	4.0	16.1	78.1	15.6	82.4	85	85
50		4.9	24.2	111.8	19.4	111.9	115	105
60		5.9	34.8	152.0	23.3	145.3	150	130
70		7.0	48.3	199.1	27.2	182.8	185	150
80		8.2	65.1	253.8	31.1	224.6	225	170
90		9.4	85.9	316.8	35.0	270.8	275	190
40	−6	3.6	14.5	73.5	15.6	79.3	80	85
50		4.5	22.0	104.7	19.4	107.1	110	105
60		5.4	31.6	141.8	23.3	138.4	140	130
70		6.3	43.8	185.2	27.2	173.5	175	150
80		7.4	58.8	235.2	31.1	212.3	215	170
90		8.5	77.3	292.6	35.0	255.2	260	190

[a]As per the model suggested by AASHTO (2011).

As an example, a typical passenger car with a mass of 1,400 kg and net power of 175 hp would consume approximately 19% of its power to overcome gravitational grade resistance on a 6% upgrade at a speed of 60 km/h. Conversely, approaching vehicles on the major road are usually moving at constant speeds (or even decelerating) and therefore they do not need extra power to accelerate; the steep grade on the major road would not have a significant effect on their performance.

Since the models presented in this paper are based on actual driver behavior and vehicle mechanical characteristics, the proposed values of ISD_{LT} requirements as presented in Tables 4 and 5 are expected to be more realistic and representative of current conditions. For an intersection that is currently designed according to the requirements of the geometric design guide (AASHTO 2011) without meeting the values suggested in Tables 4 and 5, departing drivers may fail to comfortably accelerate to 70% of the design speed of the major road without conflicting with vehicles approaching on the major road. In this case, departing drivers may need to apply larger rates of acceleration. Furthermore, approaching drivers on the major road may also need to reduce their speeds by more than the suggested value of 30% or at a deceleration rate that exceeds the suggested value of 1.50 m/s^2. The approaching drivers may also need to move to a different lane to avoid conflicting with the path of the departing vehicles. All these maneuvers that need to be taken by the approaching drivers (i.e., substantially reducing the speed, reducing the speed using a large deceleration rate, or changing lanes) may have negative impacts on traffic safety on the major road.

To test the previously described hypothesis, a statistical analysis was conducted on the records associated with 78 turning maneuvers into major roads that had high traffic volumes and/or limited sight distance (within the design values given by AASHTO). When making those 78 turning maneuvers the departing drivers applied larger acceleration rates so that they reached their target speeds within an average time of 6.3 s (with a standard deviation of 3.4 s). Conversely, an average time of 8.6 s (with a standard deviation of 4.1 s) was taken to *comfortably* accelerate to the target speeds when drivers turned into major roads that had low/moderate

Table 5. Design Values for Intersection Sight Distance for Vehicles Turning into a Four-Lane Major Road

Design speed on major road (km/h)	Major road grade (%)	t_1 (s)	d_1 (m)	d_2 (m)	L_h (m)	ISD_{LT} (m)	Rounded ISD_{LT} (m)	AASHTO $ISD_{LT}{}^a$ (m)
40	0	5.5	18.9	94.3	15.6	97.8	100	90
50		5.5	18.9	124.4	19.4	131.8	135	115
60		7.1	35.1	174.7	23.3	169.8	170	135
70		8.9	58.6	238.2	27.2	213.7	215	160
80		11.2	92.0	318.3	31.1	264.3	265	180
90		14.2	141.4	422.0	35.0	322.5	325	205
40	2	6.4	18.9	103.9	15.6	107.4	110	90
50		7.0	24.4	143.0	19.4	145.0	150	115
60		8.8	44.3	202.3	23.3	188.3	190	135
70		11.1	73.2	277.7	27.2	238.6	240	160
80		14.1	116.8	375.7	31.1	297.0	300	180
90		18.4	187.9	511.2	35.0	365.3	370	205
40	4	8.0	18.9	120.5	15.6	124.0	125	90
50		9.6	33.1	175.0	19.4	168.2	170	115
60		11.9	57.6	247.3	23.3	219.9	220	135
70		14.8	95.3	341.4	27.2	280.2	285	160
80		19.1	157.9	470.9	31.1	350.9	355	180
90		26.8	286.3	680.6	35.0	436.2	440	205
40	6	15.5	18.9	184.7	15.6	188.2	190	90
50		18.8	46.3	273.7	19.4	253.7	255	115
60		21.7	78.2	376.0	23.3	328.0	330	135
70		26.0	132.4	511.9	27.2	413.6	415	160
80		33.7	245.4	721.7	31.1	514.4	515	180
90		38.7	283.8	811.5	35.0	617.8	620	205
40	−2	5.0	18.9	87.6	15.6	91.1	95	90
50		5.0	18.9	115.3	19.4	122.7	125	115
60		5.9	28.4	155.3	23.3	157.2	160	135
70		7.4	48.2	210.6	27.2	196.5	200	160
80		9.3	75.3	278.9	31.1	241.5	245	180
90		11.6	113.2	364.2	35.0	292.9	295	205
40	−4	4.6	18.9	82.7	15.6	86.2	90	90
50		4.6	18.9	108.5	19.4	115.9	120	115
60		5.0	23.3	141.0	23.3	147.9	150	135
70		6.3	40.4	190.1	27.2	183.8	185	160
80		7.9	63.2	249.9	31.1	224.6	225	180
90		9.8	94.0	323.0	35.0	270.9	275	205
40	−6	4.3	18.9	78.7	15.6	82.2	85	90
50		4.3	18.9	103.1	19.4	110.5	115	115
60		4.3	18.9	129.4	23.3	140.7	145	135
70		5.5	34.4	174.2	27.2	173.9	175	160
80		6.9	54.1	227.6	31.1	211.5	215	180
90		8.4	80.0	291.9	35.0	253.8	255	205

[a]As per the model suggested by AASHTO (2011).

traffic volumes and overly adequate sight distance. The difference between the two means was found to be statistically significant at the 5% significance level with t-stat value of 4.788 (df = 836 and $p < 0.0001$). Based on these results, it can be concluded that drivers had to significantly increase their acceleration rates when turning into major roads that had high traffic volumes and/or limited sight distance (within the design values given by AASHTO).

By comparing the findings of this paper with those of a previous study (Dabbour 2015) that evaluated sight distance requirements for right-turn departures, ISD_{RT}, it is found that right-turn departures into major roads would usually need less distance and time to accelerate than those needed for left-turn departures shown in Tables 4 and 5, as explained in the following application examples.

Application Example

As an example to illustrate the difference between the ISD_{LT} values as suggested by the developed models and those suggested by AASHTO (2011), consider the T-intersection shown in Fig. 2(a), which is located on a two-way two-lane major road with a grade of +4% to the east and 70 km/h design speed. For left-turn vehicles, they would accelerate on 4% downgrade and therefore the left-turn sight distance, ISD_{LT}, suggested by the developed models would be 185 m. For right-turning vehicles, they would accelerate on 4% upgrade and therefore the right-turning sight distance, ISD_{RT}, as suggested by previous research (Dabbour 2015) would be 235 m. Therefore, a distance of 185 m must be cleared to the east of the intersection (to allow for left-turn departures) and a distance of 235 m must be cleared to the west of the intersection (to allow for right-turn departures). The two sight triangles where sight obstructions must be cleared are shown for both left-turn and right-turn departures.

If the grade of the intersection is reversed, as shown in Fig. 2(b), then left-turn vehicles would accelerate on 4% upgrade and the left-turn sight distance, ISD_{LT}, suggested by the developed models would be 255 m, as shown in Table 4. As for right-turning vehicles, they would accelerate on 4% downgrade and the right-turn sight

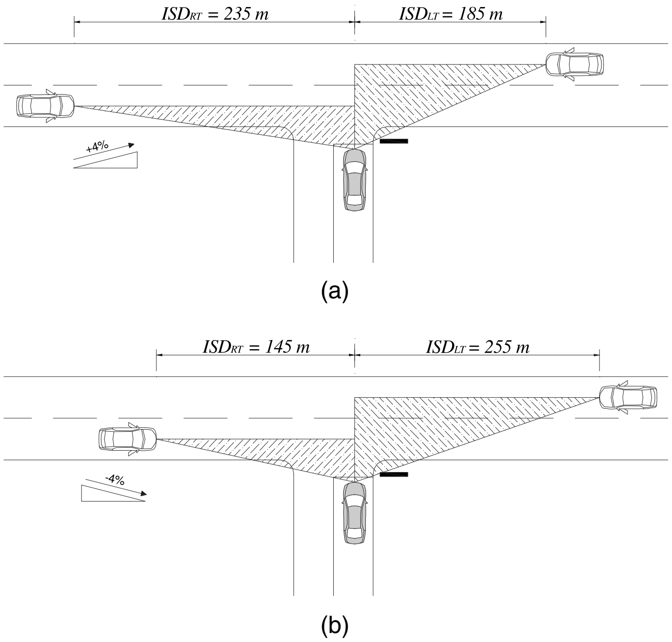

Fig. 2. Application example to determine the required ISD_{LT} and ISD_{RT} at different situations: (a) +4% Grade; (b) −4% Grade

distance, ISD_{RT}, suggested would be 145 m (Dabbour 2015). Therefore, the distance that must be cleared to the east of the intersection (to allow for left-turn departures) would be 255 m, and the distance that must be cleared to the west of the intersection (to allow for right-turn departures) would be 145 m. The two sight triangles are also shown for both left-turn and right-turn departures.

According to AASHTO (2011) and for the cases shown in Figs. 2(a and b), the distance that must be cleared to the east of the intersection is 150 m (to allow for left-turn departures regardless of the major-road grade), and the distance that must be cleared to the west of the intersection is 130 m (to allow for right-turn departures, regardless of the major-road grade). These distances are less than those suggested by the developed models. If the intersection is designed according to the minimum values of ISD_{LT} and ISD_{RT} of AASHTO (2011) without meeting the values required by the developed models, the approaching drivers on the major road may need to reduce their speeds by up to 52% by applying a deceleration rate of up to 2.84 m/s^2. Alternatively, approaching drivers may need to move to the opposite traffic lane to avoid conflicting with the paths of the departing vehicles.

Concluding Remarks

In this paper, a new method is presented to determine the required intersection sight distance at TWSC intersections based on driver behavior and current vehicle acceleration capabilities. It is assumed that the turning driver must accelerate to 70% of the design speed of the major road without conflicting with the approaching vehicles or forcing their drivers to substantially reduce their speeds or move to a different lane. The method is based on a new acceleration profile for left-turn vehicles starting from rest at TWSC intersections. The profile was developed using actual field data collected by GPS data loggers. The devices recorded the positions and the instantaneous speeds of different vehicles piloted by different drivers at 1-s intervals. Realistic ISD_{LT} values were established for different design speeds and road grades. Based on this research, the following additional remarks are offered:

1. The results of this research show that the values of ISD_{LT} suggested by AASHTO (2011) may be inadequate, especially for large design speeds and/or steep grades. By implementing the design guidelines developed in this paper, safety at TWSC intersections is expected to improve. As an example to demonstrate the implication of the findings of this paper, the average number of rear-end and side-swipe collisions related to turning departures at nonsignalized intersections in California were 1,405 and 6,261 collisions per year, respectively. These numbers are based on statistical crash data obtained from the Highway Safety Information System administered by FHWA (2016) for the years from 2004 to 2010. Implementing the new ISD_{LT} design values presented in this paper has the potential to reduce these numbers of collisions.
2. By comparing the proposed ISD_{LT} requirements presented in this paper with the requirements of intersection sight distance for right-turning vehicles, ISD_{RT} (Dabbour 2015), it is found that sight distance requirements for right-turn departures are usually less demanding than those for left-turn departures.
3. The paper provides a generic framework for calculating ISD_{LT} for TWSC intersections using any acceleration profiles other than the ones developed in this paper. Thus, the framework allows more flexibility in implementing any future acceleration profiles that may be developed due to the ongoing changes in vehicle design and drivers' characteristics and attitudes.
4. The effect of major-road grades, as shown in Tables 4 and 5, is computed based on the laws of physics as per the linear-decreasing acceleration model presented in Eq. (4). This is for the purpose of comparing ISD_{LT} requirements as suggested by the developed models with those suggested by the current design guide (AASHTO 2011). As was discussed before, there are no provisions for major-road grades in the current design guide (AASHTO 2011). Furthermore, the authors of this paper are not aware of any research studies that investigated vehicle acceleration capabilities on steep grades. Therefore, further research may be needed to investigate this topic and update the methodology presented in this paper if actual vehicle acceleration capabilities on steep grades were found to be different from the theoretical values suggested in this paper.
5. The proposed guidelines were intended for application at TWSC intersections. However, the guidelines may also be applied at signalized intersections in certain situations. One situation is when a traffic signal is to be placed during off-peak or nighttime conditions on a two-way flashing operation (i.e., flashing yellow on the major-road approaches and flashing red on the minor-road approaches). In this case, the ISD_{LT} guidelines should be provided for left-turn vehicles on the minor-road approaches.
6. The acceleration profile established in this paper is based on actual data collected by different drivers with different vehicle types using GPS data logging devices that recorded the positions and instantaneous speeds of turning vehicles. The profile was used to develop improved ISD_{LT} values for left-turn vehicles at TWSC intersections. However, the profile can also be used whenever there is a need to understand acceleration behavior of vehicles turning left starting from rest, such as computing the length of left-turn phase at signalized intersections where the initial (turning) acceleration segment of the profile would be useful.

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