Updated Traffic Flow Dispersion Model Considering Effects of in-Vehicle Advisory Messages

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Abstract

Traditional dispersion models; such as the travel time distribution based normal distribution model and geometric distribution model; are dedicated to traffic situations with conventional traffic signs and signals; which may not be able to depict the platoon dispersion phenomenon under a connected vehicle system with in-vehicle advisory messages. This research re-examines the traditional dispersion models with suitable adjustment considering impacts of in-vehicle messages. A correction factor was employed to update the travel time distribution model; while travel time distributions of leading vehicles with and without the in-vehicle messages were simulated in a driving simulator with forty-five subjects tested. Parameter calibrations for travel time dispersion of traffic flow in work zone and intersections with sun glare were conducted to illustrate the entire modeling and calibration procedure. With more practical simulations and field tests; the flow dispersion models can be further calibrated for more applications in traffic flow simulation and optimizations.

Keywords: Dispersion model; Platoon dispersion; Travel time distribution model; In-vehicle messages; Work zones; Intersection; Sun glare

Introduction

Platoon dispersion of traffic flow is the deterioration in platoon integrity that changes the compactness of a platoon. There are several measures of platoon dispersion: 1) the change of gap between the same pairs of vehicles when travelling towards downstream; 2) the change of headway; 3) the change of traffic flow rate within portions of the platoon, which is the most commonly used measure of dispersion; or 4) the change of density in different portions of platoon. Dispersion is a function of the length of the platoon and the travel time from a given point to a downstream location (or sometimes a downstream stop-line) [1]. Obviously the longer the travel time is, the greater the dispersion would be as the longer the travel time would provide longer time (opportunity) for different drivers to deviate from the average travel time. For a given distance over a roadway segment (such as the distance between two traffic signals), there will be more dispersion of a slow speed traffic flow than that of a higher speed one. Typical flow dispersion models include the Normal Distribution Model by Pacey [2], the Geometric Model by Robertson [3], and the Neural Network System Identification Model by Qiao [4]. Some of these dispersion models have by now been incorporated into the famous traffic simulation and signal timing optimization programs such as TRANSYT (Traffic Network study tool) [5] and TRANSYT-7FTM [6], which are now widely used in the world for routine operations of traffic signals by serving millions of the public every day [4]. Since then, the calibration and implementation of traffic flow dispersion models seem to be a well-developed technology already [4,7,8].

However, in recent years, many innovative technologies in communication and computer engineering have advanced not only the revolution of vehicle designs, but also the operation of transportation systems. For example, the Connected Vehicle (CV) and Vehicle-to-Infrastructure (V2I) technologies could change drivers' behaviors, especially when vehicles are approaching the areas with traffic control guidance such as the work zones and intersections [9-11]. The space distributions of vehicle speeds, acceleration rates, the travel time, and thus the ways of dispersion could be totally changed [12-14]. Therefore, there is a need to re-examine the traditional traffic flow dispersion models, and make suitable adjustment accordingly.

With regard to this, this research is proposed to calibrate travel time based traffic flow dispersion models. A travel time factor was proposed to update the traffic flow dispersion model for the application of the V2I based Drivers' Smart Advisory System (DSAS). Driving simulator tests were conducted in simulated sequential intersections with sun glare disturbance as well as within a typical work zone area. The exact travel time and average driving speed of the leading vehicles that are instructed by the DSAS in the two study sites were recorded. Meanwhile, field observations were carried out at the intersection of NASA@HS 146, Webster Texas, and within the work zone area in Bellaire Blvd, in Houston Texas, to collect the driving speed variation of the vehicle platoon. A total of seventy-five subjects were recruited for the driving simulator tests, and the model parameters were carefully calibrated. The difference in the travel time distributions were visualized and compared.

Traffic Flow Dispersion Models

Normal distribution model

The diffusion theory proposed by Pacey [2] and investigated in detail by Grace and Potts [15] have shown to be adequate in describing the spreading of platoons in medium traffic flow without interference. According to Pacey’s model, vehicles in a platoon travel in speeds $v$ with mean $\mu$ and standard deviation $S$. The arrival flow at the downstream section is the combination of the flows traveled from the upstream flow section and standard deviation $S$. The arr...
Reformatted equation (3) in a geometric distribution form:

\[
q_d(j) = \sum_{i} q_0(i)g(j-i)
\]  

(1)

where, \(q_0(i)\) is the upstream flow rate at time i; \(q_d(j)\) is the downstream flow rate at time j; \(g(T)\) is a special normal distribution function of travel time as defined in equation (2).

\[
g(T) = \frac{a}{T^2S\sqrt{2\pi}} \exp\left[-\frac{(a/T-\bar{v})^2}{2S^2}\right]  
\]  

(2)

where,

- \(T\): Travel time between upstream and downstream points;
- \(a\): A counter of time interval at the upstream point;
- \(j\): A counter of time intervals at the downstream point;
- \(t\): 0.8 times the mean travel time;
- \(\bar{v}\): Average speed;
- \(S\): Standard deviation of the travel speed.

**Geometric distribution model**

An alternative method for predicting platoon dispersion has been given by Robertson [5], who used observed data to derive an empirical method of predicting the platoon behavior. The method was used for synchronization of traffic signals for minimum delay [16]. For each time interval it is assumed that the arrival flow at the downstream stop-line is found by the following recurrence equation:

\[q_d(j) = Fq_0(j) + (1 - F)q_d(j-1).\]  

(3)

Intelligent dispersion model

Qiao et al. proposed an intelligent dispersion model based on a nonlinear mapping of a multi-input one output dynamic system, which is actually a one hidden layer feedforward sigmoid neural network model. The information set of the established neural network model is as:

\[Z^n = \{ y(t-1), \ldots, y(t-n_1), u(t-k), \ldots, u(t-k-n_2), u(t-k-n_3), \ldots, u(t-k-n_4)\},\]  

(6)

where, \(Z^n\) represents the information set of all available data, \(y\) represents the downstream flow with \(n_1\) observed data, \(u\), and \(u\) are the upstream flow and upstream speed, respectively, and \(n_2\) and \(n_3\), and \(n_4\) are the length of the past upstream flow and the past upstream speed to be used as inputs to the neural network, respectively. \(k\) is the time delay. Normally, \(n_i\), \(n_j\), and \(n_k\) are called the orders of model. The predictor is:

\[\hat{y}(t|\hat{\theta}) = \hat{y}(t/t-1, \hat{\theta})\]  

(7)

where, \(\hat{y}\) is the predicted value of parameter set. The neural network model under such regressors is called the Series-Parallel model [20] or the NNARX model [21].

In equation (7), \(\hat{y}(t|\hat{\theta})\) is a “guess” of downstream traffic flow \(Y(T)\), providing that the information in \(Z^n\) and the particular parameter value \(\hat{\theta}\) are given.

**Calibration of flow dispersion model from travel time distribution with V2I**

In connected vehicle system, many studies demonstrate that the V2I messages would influence drivers’ driving behavior, thereby altering vehicle speeds and accelerations [22-24]. Vehicles’ travel time could also be changed accordingly. The travel time distribution \(g(T)\) in equation (2) for normal distribution model and the smooth factor \(F\) in equation (3) for geometric distribution model would be varied. Assuming that the travel time with V2I is \(T_{V2I}\) a time correction factor can be introduced and calculated as:

\[\gamma = \frac{T_{V2I}}{T}\]  

(8)

Thus, the calibrated travel time for normal distribution model is updated to:

\[g(T) = \frac{a}{(\gamma T)^2S\sqrt{2\pi}} \exp\left[-\frac{(a/T - \bar{v})^2}{2S^2}\right]\]  

(9)

and the transformed normal function of travel time is now replaced by the geometric distribution [18], Rumsey and Hartley [19] proved that the geometric distribution has a longer tail than the corresponding transformed normal distribution, which means the geometric distribution model predicts a wider platoon dispersion for any given mean travel time. Therefore, the distribution range of vehicles travelling according to the geometric distribution model is wider than that from the normal distribution model.

**Intelligent dispersion model**

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**Calibration of flow dispersion model from travel time distribution with V2I**

In connected vehicle system, many studies demonstrate that the V2I messages would influence drivers’ driving behavior, thereby altering vehicle speeds and accelerations [22-24]. Vehicles’ travel time could also be changed accordingly. The travel time distribution \(g(T)\) in equation (2) for normal distribution model and the smooth factor \(F\) in equation (3) for geometric distribution model would be varied. Assuming that the travel time with V2I is \(T_{V2I}\) a time correction factor can be introduced and calculated as:

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Thus, the calibrated travel time for normal distribution model is updated to:

\[g(T) = \frac{a}{(\gamma T)^2S\sqrt{2\pi}} \exp\left[-\frac{(a/T - \bar{v})^2}{2S^2}\right]\]  

(9)

The calibrated smooth factor of geometric model is:

\[F = (1 + \alpha\gamma T)\]  

(10)

The newly introduced parameter \(\gamma\) can be calibrated from observed data. Since the V2I is still in its infant testing stage, the field test is not feasible. A driving simulator test could be one of possible options to calibrate the \(\gamma\).

**Testing travel time dispersion in simulator test**

Driving simulator tests were chosen to measure the impacts of V2I message on the travel time of a leading vehicle. Meanwhile, speed standard deviation of a vehicle platoon was measured by field observations on an approach to an intersection and a work zone.

**Apparatus**

In this research, a fixed-base driving simulator (Drive Safety DS-600C) was employed, while the sun glare was artificially mimicked through an overhead projector as is illustrated in Figure 1.
Scenario design and test procedure for test bed at intersections with sun glare effects

Three scenarios were designed for the driving simulator test. Each scenario is coded with two letters in relation to two factors: (a) with sun glare (S) or without (\(\bar{S}\)); and (b) with the DSAS AWM (D) or without (\(\bar{D}\)). Figure 2 shows the layout of the scenario design with corresponding unique code. Each subject was requested to drive on a virtual track of approximately 3,000 meters in an industrial area. The speed limit on the track is 45mph (72 km/hr). As Figure 2 illustrated, there are three intersections. The distance between two sequential intersections is about 1,000 meters. Subjects experienced the situation with and without sun glare disturbance, and with and without DSAS warning message under sun glare effect at each intersection, respectively. The DSAS messages include “Red Light is On” and “Green Light is On”, which last about 1 second. During the test, each subject was the only driver on the track. The only one visual disturbance is the sun glare in the simulation environment.

The determination of locations to provide audio messages was based on human’s perception-reaction time 2.5 second \([24,25]\) (Travel distance in reaction time: \(D_a\)), the duration of the audio messages (Travel distance in audio playtime: \(D_p\)), and minimum sight distance (\(D_s\)) for the specific speed limit \([26]\) (Figure 3). Therefore, for the speed limit of 72 km/hr, the total signal message distance of \(D_{sm}\) is:

\[
D_{sm} = D_a + D_p + D_s = 20m + 50m + 140m = 210m.
\]

Besides, the approach of each intersection was divided into three segments for speed deviation measurement.

Scenario design and test procedure for test bed in work zone

Figure 4 shows two scenarios designed for the work zone simulator test. Each work zone was divided into four segments for speed deviation measurement. Subjects drove through two work zones with and without the aid of DSAS messages, respectively. In the scenario with the DSAS messages, subjects received audio messages on the traffic control signs, such as “Workzone Ahead”, “Speed Limit Is 30 Mph”, and “Right Lane Is Closed”. The distance to provide the audio messages is determined by the 2.5 seconds perception-reaction time \([27,28]\) the duration of the audio messages (less than 1 second), and the speed limit.
Participants

Individual driving behaviors could be also subject to their demographic information, such as gender, age, and education level [29,30]. Therefore, subject recruitment was based on Houston demographics from 2010 census (Table 1). A total of 30 and 45 subjects were recruited for the driving simulator tests of intersection with sun glare and work zone, respectively. All subjects possess valid C class Texas driver license and have self-reported of normal or corrected-to-normal visions, and don’t have any hearing problem.

Data collection and processing tools

During the driving simulator tests, the leading vehicle’s real-time operation information was collected at a sampling rate of 60 Hz under the situation with and without the aid of the V2I DSAS messages. The collected operation information includes vehicle’s geo-location, speed, and braking levels ranging from 0.0 to 1.0 (0.0 is the minimum with no brake and 1.0 the maximum with full brake). The collected data were processed to measure drivers’ driving performance through a self-developed program in MATLAB, in terms of travel time and driving speed.

Field observations

Two field observations were conducted to obtain the speed deviations. The field observation I was carried at the intersection of NASA @ HS 146, Webster, TX. Video of vehicle movements on southbound approach were recorded from Houston Tran Star from 10:00 AM to 11:20 AM on August 20, 2014. A test vehicle started from 1,000 meters away the stop line of the downstream intersection and randomly joined in a vehicle platoon to approach the intersection. The test vehicle’s speeds were measured at 210 meters, 190 meters, 140 meters, and zero meters (at the stop line), respectively, which were within the active area of the DSAS messages as shown in Figure 3. After passing the intersection, the test vehicle turned back to the start point for another round.

Field observation II was carried out within a road construction zone in Bellaire Blvd. in Houston, Texas, on August 21 in 2014. A test vehicle started from 1,480 meters (zero in Figure 4) away the work zone buffer area (the right lane is complete closed) to randomly join a vehicle platoon. The work zone buffer area was about 500-meter long. The test vehicle went through the work zone area and turned back to the start point for another round. The speeds were recorded at 700 meters, 600 meters, 270 meters, 100 meters, and zero meters to the work zone buffer area, respectively.

The sample size (N) of the joined vehicle platoons was determined using Equation (11) [31,32].

\[ N = \frac{S^2 \cdot Z^2}{E^2} \]  

(11)

Where,

- \( S \): Standard deviation;
- \( Z \): z-score;
- \( E \): Acceptable errors.

Based on preliminary study, the \( S \) was approximately 7%. When the \( Z \) was set to 1.96, the sample size is able to meet a 95 percent conference level. In this study, 5% errors (E) was acceptable for driving speeds. It turns out that a minimum of 8 samples of vehicle platoons was required.

Testing Results

Intersections with sun glare disturbance

Distribution of the first vehicle from simulator tests and estimation of time factors: Figure 5 displays the travel time distribution of the first vehicle in each segment from simulator tests for three scenarios. As a whole, the travel time deviates widely with the increase in travel distance along the approach to an intersection. The deviations are obviously caused by the sun glare disturbance and the application of DSAS that is proposed to offset the sun glare interference.

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time during the segments in the first 400 m away to the intersection are compared in Table 2.

In Table 2 for segment 1, the average travel time with sun glare $sD$ (13.97s) is shorter than that without sun glare $SD$ (17.70s). When the DSAS is applied in the scenarios $SD$, the travel time is compensated back to some extent (15.14s). The time factor $\gamma$ for the sun glare scenario is 0.79, while for the scenario of sun glare with DSAS message is 0.86.

Similar phenomenon can be found for segments 2 and 3, although the differences of travel time among different scenarios are normally less than 1s.

Field calibration of speed standard deviation at intersection approach: Table 3 lists the calculated mean speeds and standard deviation for the approach to the intersection from field observation I. Along with the approach to the intersection, the mean speeds decrease with higher standard deviations.

Comparison of travel time distributions with sun glare and DSAS messages: Figure 6 demonstrates the resulted travel time distribution based on normal distribution model in Equation (9) using the estimated average travel time and time factors $\gamma$ in Table 2 and the observed speed deviation in Table 3. In Figure 6 for segment 1, scenario $SD$ represents the normal situation with no sun glare and no V2I DSAS message (the blue line). The time factor $\gamma_{SD}$ is 1.00. In this case, Equation (8) is the same as Equation (2). For scenario $S$ and $SD$, however, $\gamma_{SD} = 0.79$ and $\gamma_{SD} = 0.86$. The calibrated model in Equation (8) is used to calculate vehicle travel time (the red line and green line, respectively). The green line lies in between the red and blue lines, which means the V2I DSAS messages offset the difference caused by the sun glare disturbance at a certain level.

For segments 2 and 3, the time factors $\gamma$ are all close to 1.00 and their speed standard deviations are close to each other as well. This implies that the impacts of both sun glare disturbance and V2I DSAS message are not so obvious, whether or not to use the calibrated dispersion models makes no significant difference.

Work zones

Distribution of the first vehicle from simulator tests and estimated time factors: Figure 7 shows the travel distribution of the first vehicle with in the work zone from the simulator tests. With the approaching to the work zone entrance, the distribution of travel time with DSAS message becomes narrower.

Field calibration of speed standard deviation: Table 5 lists the
in Table 4, and the speed standard deviations in Table 5. Significant deviation of vehicle speeds normally shows up in this area. The time factors \( T \) for the intersections and work zones are inconsistent in different situations, which means the travel time \( T \) in the traditional normal distribution models as well as in the geometric distribution models may not be able to provide a realistic result for vehicle platoon dispersion. The calibrated model is able to accurately express the dispersion evolution with the V2I DSAS message. With more practical simulations and V2I field tests, the flow dispersion models can be further calibrated for more applications in traffic flow simulation and optimizations.

### References


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<th>Segment 3</th>
<th>Segment 2</th>
<th>Segment 1</th>
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<td>33.79</td>
<td>45.05</td>
<td>47.87</td>
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<td>Std. Dev (m/s)</td>
<td>2.31</td>
<td>7.54</td>
<td>3.43</td>
<td>1.75</td>
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Table 5: Speed standard deviation in work zone.

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