Modeling Passenger Vehicle Acceleration Profiles from Naturalistic Observations and Driver Testing at Two-way-stop Controlled Intersections

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ABSTRACT

A primary goal of crash reconstruction (or collision avoidance system) is to determine whether a crash is avoidable or not. A prerequisite for the determination of avoidance is knowledge of the time that is available to a driver. In a path intrusion crash scenario, a method to determine the time available for a major road driver is to know the time a minor road driver accelerated before impact. This research is an attempt to model the time based upon acceleration distance.

The current study involved two parts. Part one was a naturalistic study of driver acceleration behavior at two-way-stop controlled intersections. In part two, ten drivers with instrumented vehicles were asked to drive a route that included four acceleration runs at two-way-stop sign control intersections. In the naturalistic study, the accelerations were measured using video recordings and videogrammetry at known distances.

The purpose of the research was to gather acceleration data that was used to develop mathematical models that offers crash reconstructionists (and collision avoidance systems) the time duration of an acceleration given the distance to travel and the location of the accelerating vehicle along the acceleration profile.

The result was that drivers accelerate at a non-linear rate from two-way-stop controlled intersections. Duration of acceleration was best modeled with respect to distance (time *versus* distance) with a power function. Acceleration distance *versus* time and speed *versus* time models are also offered. These results were compared to results from prior acceleration research that was conducted at similar and different intersections.

INTRODUCTION

Vehicle acceleration over a known distance offers information regarding the time of acceleration. The time a minor road driver accelerates from a stop sign area to impact offers information regarding the time available for a major road driver to respond. Given the time available to a driver, a crash reconstructionist may then determine if the driver on the major road could avoid the crash or not. As an example, if an intruding driver accelerated 5 m (16 ft) into the major road in 2 seconds and we learn that a typical driver on the major road needs two seconds to respond (perception-response time), then no time would be available for an avoidance maneuver and that crash scenario would be unavoidable for most drivers. Knowledge of the time available to a driver may also be vital information for a collision avoidance system. Another use of average acceleration and the variance of accelerations would be to determine the probability of a driver stopping before entering an intersection.

A driver's acceleration varies throughout the acceleration process. One of our primary goals is to determine the duration of the acceleration. To that purpose, the average or nominal acceleration factor utilized by a crash analyst should account for the portions of the acceleration profile that were part of a driver's pre-impact acceleration. Long [1] reported that "Design accelerations were found to deviate substantially from observed accelerations" (p. 58). Further, normal acceleration has been found to be more closely related to driver preference rather than vehicle capability [1]. Therefore driver acceleration behavior models for the purposes of crash reconstruction have yet to be produced.

Of interest are the acceleration curves or the manner in which acceleration changes. Previous research [1, 2, 3] has shown that driver accelerations in traffic involve three phases. Phase one is the initial slow phase in which the foot moves from the brake to the acceleration pedal and the pedal is depressed. Phase two involves a linear (or near linear) acceleration. Phase three involves a decreasing acceleration as the driver reaches his or her desired speed.

The American Association of State Highway and Transportation Officials (AASHTO) [5] assumes a piecewise linear acceleration, meaning that they assume linear accelerations for different phases of the acceleration. Long [1] indicated that the AASHTO Model is based upon research by Harwood [6] which utilized a trap between 61 and 122 m (200 and 400 ft) from the start of the acceleration and noted that most drivers will accelerate to 40 km/h (25 mph) before reaching the start of the trap at 61 m (200 ft).

Some acceleration models are concerned with the acceleration of vehicles to speeds near the speed limit; the research by Long [1], Hong [4], and Wang [7] modeled accelerations up to 60 km/h (37 mph). Bonneson [8], for instance, was concerned with the acceleration of vehicles on highway on-ramps, which involved a much higher desired constant speed than is common at most intersections. Happer [9] studied the trajectory and movement, including acceleration of left-turning vehicles at a signalized intersection. Many of the available models neglect the initial (slow) portion of the acceleration. Fugger [10] and Proctor [11] did address the slow acceleration at the initial phase.

On the basis of the literature, acceleration behaviors change at four-way-stop controlled intersections [7, 9, 10], two-way-stop controlled intersections [12, 13, 14], and at arterial entrances [15]. Further, accelerations change from an initial slower phase, to a more linear acceleration to a gradual tapering off phase. Therefore, the average acceleration will differ at different type intersections and will also differ during various phases of the acceleration. This research will build upon the research of others while specifically dealing with a common crash scenario by addressing acceleration at two-way-stop controlled intersections.

Several papers have reported that drivers exhibited linear decreasing acceleration profiles [1, 3, 7, 8]. A linear decreasing model assumes that drivers start at a peak acceleration and acceleration gradually decreases to zero. The linear decreasing model was based primarily upon research in which drivers were accelerating longer distances, such as along highway on-ramps. The time or distance necessary to reach peak acceleration was not addressed in the linear decreasing model because it was not a significant factor in a long acceleration and because most research involved data collection at one sample per second. At a sampling rate of one per second, an initial slow acceleration is neglected.

If a minor road driver accelerates from a stop for five seconds or less, an initial slow phase of acceleration may not be ignored, even if it occurs for less than a second. This research will attempt to develop models for driver acceleration that reflects the behavior of drivers at two-way-stop-controlled intersections. Two primary studies were conducted:

1. A naturalistic study, where 244 unaware drivers were observed and vide recorded.

2. Driver testing, where 10 drivers were tested in instrumented vehicles along a route that included two-way-stop sign control.

The distance from the minor road stop line to the major road centerline was measured at several intersections. Based on our observations, the most common acceleration distances were 7.5 m (24.6 ft) for crossing one lane and up to 15 m (49.2 ft) when crossing two lanes. Since the latter acceleration distance data will capture the former, our goal was to capture at least 7.5 m of acceleration distance and preferably 15 m in the naturalistic study.

For the purposes of this research, acceleration will be reported in terms of g (gravitation units; acceleration m/s^2 divided by gravity). The acceleration duration discussed is from the first moment the vehicle starts moving to acceleration durations of 3 s in the naturalistic study and up to acceleration durations of 5 s in the driver testing study. Therefore, this research will focus upon the first two phases of the acceleration. The models presented (for acceleration durations of 1 to 5 seconds) were based on the data from the driver testing which was consistent with the data from the naturalistic study. Previously mentioned studies are in agreement that the final phase of the acceleration can be modeled with a linearly decreasing function.

METHODS

PART 1: NATURALISTIC STUDY

Experimental Set-Up

For this study, eleven two-way-stop sign-controlled intersections in the greater Toronto, Canada area (within about 100 kilometers) were selected. The intersections selected for the study were located in primarily rural environments, flat; without significant curves or elevations. The major roadways had an 80 km/h speed limit and the intersecting secondary roadway had 60 to 80 km/h (37 to 49 mph) speed limits. These intersections appeared to have relatively high traffic volumes. A total of 244 minor road vehicles were observed, videotaped and analyzed for speed and accelerations. Video recording was conducted for a period of 10 to 20 minutes at each of the eleven intersections. Between 12 and 20 drivers were analyzed for each of the intersections. Only vehicles travelling straight through the intersection were included in our analysis. All vehicles that turned left or right at the intersections were ignored.

The vehicles were observed as they approached the stop sign/ stop line area until they moved well into the intersections (up to 15 m) and/or out of camera range. We captured the initial few seconds from the moment the vehicles started moving to the point that the vehicle moved about 3 seconds into the intersection. Please note that many vehicles continued accelerating more than 3 seconds into the intersection, however in several instances, their view was obstructed by traffic travelling in the opposite direction; hence we reported on the initial 3 seconds of acceleration in this study.

A camera with digital video recording capabilities of 30 frames per second was utilized. The camera was set on a tripod and was placed near each intersection, perpendicular to the motion of the vehicles. The observations were made during favorable lighting and environmental conditions, with the exception of one intersection, which was observed during the day and at night. The experimenter was visible to drivers when collecting data; however, this did not appear to affect driver behavior.

Evaluation of Measurement Technique

Before collecting data, pilot tests were conducted to determine the accuracy of the videogrammetry method utilized in the analysis. Video data of an instrumented test vehicle was captured and analyzed. The instrumentation included two accelerometers, which were both placed near the center of gravity of the vehicle. The sampling frequency of the accelerometers was 100 Hz. The vehicle speed was calculated by integrating the acceleration of the accelerometer data and the accelerometer-specific software reported speeds. The instrumentation utilized were a Race Technology DL1 which contains a 100 Hz accelerometer and 5 Hz gps data logging unit, and a Gtech Pro which is a 100 Hz accelerometer and data logger.

Slow, gradual and abrupt acceleration tests were conducted with an instrumented test vehicle, videotaped and analyzed via the methodology presented in this paper. The video analysis software, Vernier Logger Pro, was utilized to create a two dimensional graphical representations of the motion seen in the video to mathematically analyze the events. A comparison of the vehicle wheelbase with the same distance on the video was performed as a way to verify scale. Points were traced manually and directly on selected targets on the videos (such as the center of the wheel). The software automatically entered the position coordinates into a spreadsheet. The results were graphed as can be seen in Figure 1. Analysis was conducted on each data set to determine the distances and speeds traveled over each time period.

At speeds greater than 1 to 2 m/s, the difference between the speed assessed using videogrammetry and that from the instrumented vehicle was between 5 and 10% overall. During the first second of acceleration, there was greater variance, but that variance reduced to less than five percent at acceleration durations of 3 s or more. These results suggest that videogrammetry is an effective method for measuring vehicle movements for the duration of acceleration in this research, similar to other research [9, 10, 12].

<figure 1 here>

Observations and Results

During the study, traffic approaching the stop sign frequently did not stop or did not stop near the stop line. Generally, the traffic was observed to stop ahead of the stop sign or stop line, such that the front of the vehicle was set back from the intersecting roadway by a few meters as seen in Figure 2 below.

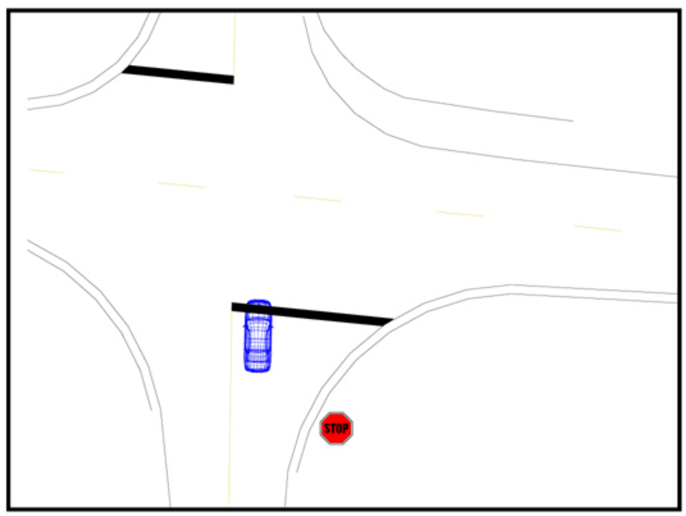

Figure 2. Top view of typical driver stopping position at intersection 9.

Screen captures of typical stopping position and acceleration for a vehicle at intersection #3 is depicted in Figure 3 and Figure 44. In Figure 3, the stopping location of the vehicle is approximately 2.0 to 2.5 m from the edge of the road which is consistent with prior research [6, 12] who found that the typical stopping location of vehicles is with the front of their vehicle 1.7 to 2 m (5.7 to 6.5 feet) from the near edge of traveled lane.

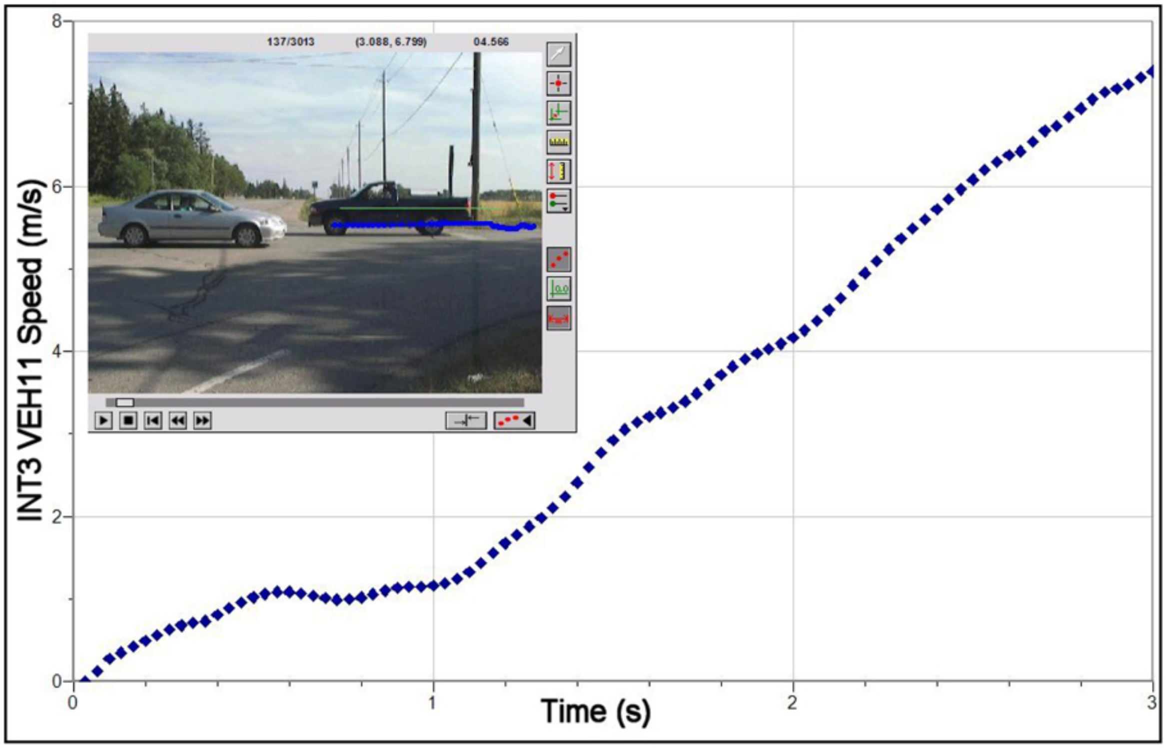

Figure 1. A screen capture of the speed graph for a trial at intersection #3. Note that the vehicle accelerated from a stop.

Figure 3. Typical stopping position for vehicles at intersection number 3.

Figure 4. View of the position of the vehicle seen in Figure 3 ***at approximately 2 seconds after the vehicle starts moving.***

Vehicles were observed to either stop completely before entering the intersection, or they came to a “rolling stop” before entering the intersection. A “rolling stop” was one where the drivers rolled through the stop sign (or stopping) area at a relatively low speed (about 1 to 2 m/s) prior to accelerating across the intersection. The drivers appeared to check for traffic in the proximity of the intersection and then accelerated. There were several instances of queuing of vehicles at the stop signs. A small percent of vehicles did not stop and rolled through the stopping area at almost 4 m/s, when there were no approaching vehicles on the major road. The vehicles that rolled through the stopping area did not exhibit an initial slow roll (phase 1 of the acceleration process) and their accelerations were not considered in the analysis.

Of the 244 vehicles observed, 179 drivers came to a complete stop prior to accelerating. Therefore, most of the observed drivers in this research made complete stops, as there was often approaching traffic on the major roadways. Approximately 27% (65 vehicles) did not stop prior to accelerating. Almost all of the 65 drivers that did not come to a complete stop were at higher traffic volume intersections and were approaching the stop sign from a queue of vehicles. These drivers appeared to take advantage of a gap in the major roadway traffic. Therefore, many of the vehicles that did not stop before the road edge had stopped at some time earlier.

We also noted that the acceleration from a stop was not linear. Vehicles that accelerated from a stop displayed the multi-phase acceleration observed by other authors [1, 2, 3, 5, 6, 10, 11]. Drivers accelerated at a relatively slow rate initially and accelerated more aggressively after one second.

During the initial phase of the acceleration, the average acceleration was 0.07 g with a standard deviation of 0.04 g. The initial phase usually occurred over a time period of approximately 0.90 seconds +/− 0.40 seconds. The average secondary acceleration value (after the initial phase through to 3.0 seconds after the start of acceleration) was 0.25 g and the standard deviation was 0.06 g. The overall average acceleration for both phases (to the end of the 3.0 s acceleration duration) was 0.21 g with a standard deviation of 0.06 g (see Table 1).

Table 1. Accelerations and durations observed during the naturalistic study.

	Phase 1	Phase 2	Overall
Rate (g)	0.07 ± 0.04	0.25 ± 0.06	0.21 ± 0.06
Duration (s)	0.90 +/- 0.40	2.1 +/- 0.40	3.0

The average, 15th percentile and 85th percentile vehicle speeds at various times (from all observed drivers who stopped) is shown in Figure 5.

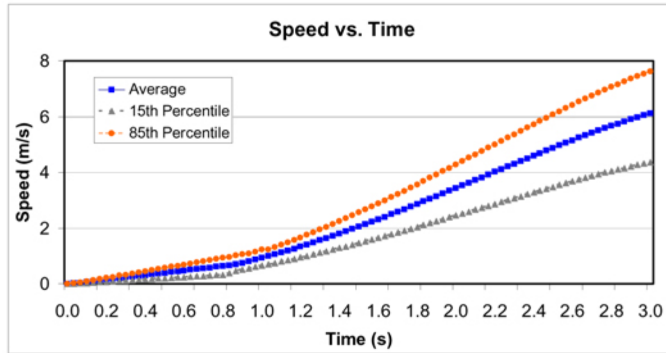

Figure 5. Average, 15th percentile and 85th percentile vehicle speeds vs. time trend for the observed vehicles (179) in the naturalistic study.

PART 2: DRIVER ACCELERATION TESTING

Experimental Set-Up

We conducted testing of 10 drivers at several intersections that included 2 two-way-stop controlled intersections. The drivers were not aware of the specific reason for the testing but were told that they were part of driver research. The drivers were instructed to drive normally, and come to a complete stop prior to accelerating. Drivers accelerated through each of the intersections in each direction (at each of the intersections) on the minor road in an instrumented vehicle (their own or a test vehicle if they opted for it). The instrumentation was the same as in the *EVALUATION OF MEASUREMENT TECHNIQUE* section. Forty test runs were recorded. One acceleration event was not included. During one acceleration event the driver accelerated, and then braked for a vehicle on the major road. Therefore, the results are based upon 39 accelerations.

Observations and Results

During the initial phase of the acceleration, the average acceleration was 0.08 g with a standard deviation of 0.04 g. The initial phase usually occurred over a time period of approximately 0.90 seconds +/− 0.20 seconds. The secondary acceleration value (after the initial phase through to 4.1 seconds after the start of acceleration) was 0.24 g and the standard deviation was 0.05 g. The overall average acceleration for both phases (through the acceleration duration of 5.0 s) was 0.21 g with a standard deviation of 0.05 g (see Table 2).

Table 2. Accelerations and durations observed during driver testing.

	Phase 1	Phase 2	Overall
Rate (g)	0.08 ± 0.04	0.24 ± 0.05	0.21 ± 0.05
Duration (s)	0.90 +/- 0.20	4.1 +/- 0.20	5.0

The delineation of the phases of acceleration may be seen when acceleration versus time is plotted in Figures 6 and 7 below. There is an initial slow acceleration up to 0.6 seconds, followed by a more aggressive acceleration increasing to a peak of 0.30 g and then a linear decreasing slope. After peak acceleration is attained, acceleration decreases at a rate of 0.04 to 0.05 g per second. The shoulder between the increasing acceleration and the decreasing acceleration occurred approximately 1.6 seconds after the vehicle started to move as can be seen in Figure 7 below.

Figure 8 below shows the relationship of speed versus time from the driver testing; the speed increases slowly during the first 0.9 seconds and then increases more significantly. As the vehicle reaches the desired speed, and acceleration starts to decrease to zero, the speed versus time line begins to flatten out.

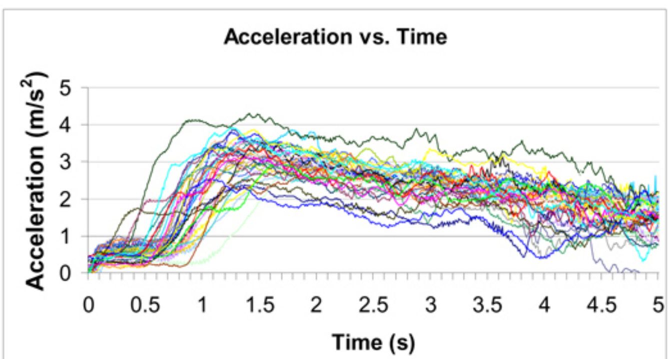

Figure 6. 39 vehicle acceleration profiles from 20 drivers during the driver testing at a two-way-stop controlled intersection.

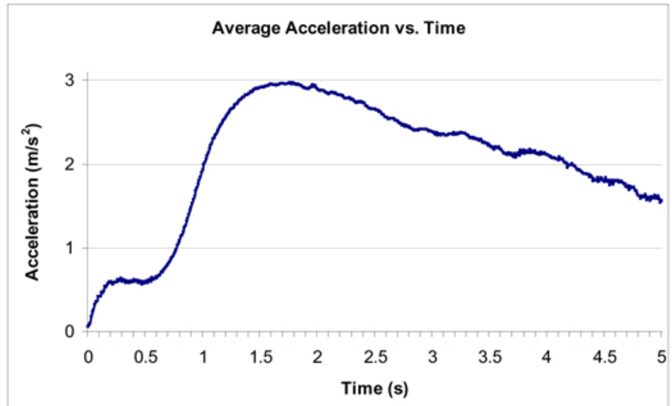

Figure 7. Average vehicle acceleration during the driver testing at a two-way-stop controlled intersection.

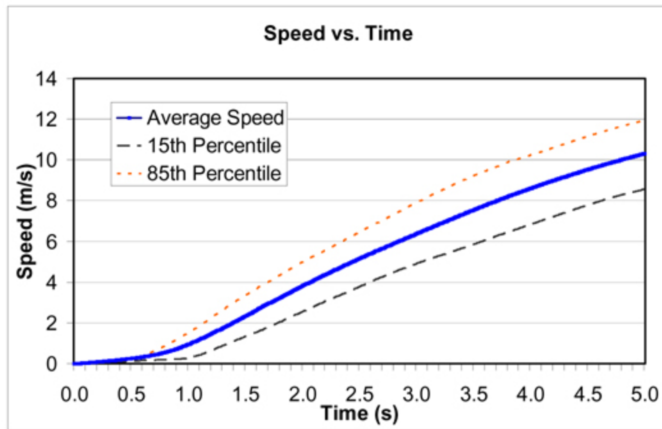

Figure 8. Vehicle speed during acceleration from a stop during the driver testing at a two-way-stop controlled intersection.

Comparison Of Naturalistic Results With Instrumented Vehicle Results

As can be seen in Figure 9, the data gathered during Part 1 (the naturalistic study) was virtually identical to the data gathered during Part 2 (the driver testing). This confirms that driver acceleration behavior; in the context of this paper, is relatively consistent under similar circumstances. These results corroborate other research [1] that showed that driver acceleration is a choice rather than a factor based by vehicle capability.

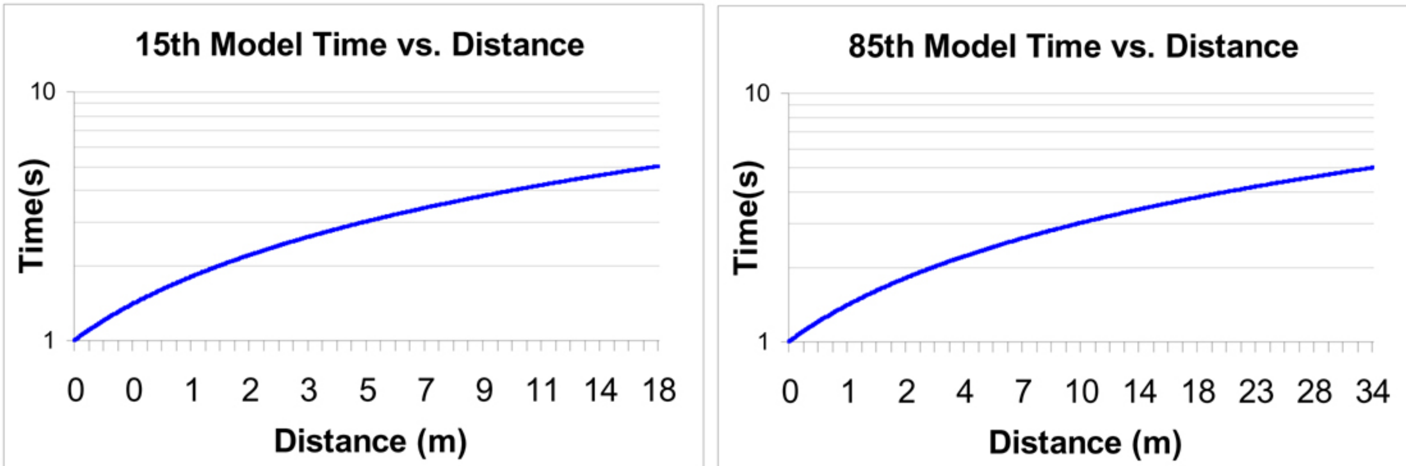

Figure 11. 15th and 85th percentile time vs distance models.

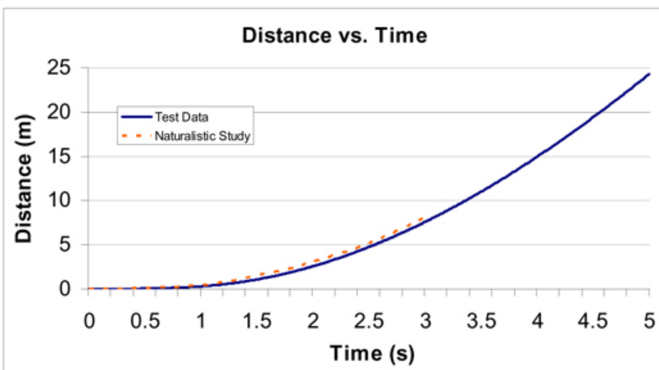

Figure 9. Distance versus time graph (naturalistic and driver test data) for two-way-stop controlled intersections.

DRIVER ACCELERATION MODELS

Time-Distance Model

While most models address acceleration in terms of velocity and time, in a crash reconstruction both velocity and time are frequently unknown. A crash reconstructionist may know the acceleration distance (stop location to impact), and from there will likely want to know the time of the acceleration. The average time to travel a specific distance can be seen in Figure 10 below. The average, 15th and 85th percentile acceleration profiles are relatively consistent in profile which suggests the difference is most likely related to a constant (See Figure 11). Please note that the time axis in Figures 10 and 11 are logarithmic; to better illustrate the power relationship. As can be seen in Figure 9 above, during the naturalistic study or the driver testing, the vehicles travelled a very short distance (less than 0.60 m) during phase 1. Given the stopping positions of the vehicles of 2.0 to 2.5 m from the edge of the road, it did not appear that a vehicle would intrude into the major road during phase 1. Accordingly, the time axis starts at 1 second and the models discussed below are for acceleration durations of 1 to 5 seconds.

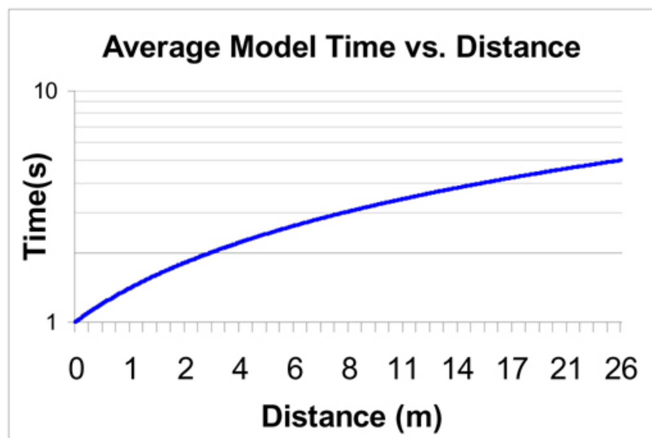

Figure 10. Average time versus distance model.

<figure 11 here>

Trend analysis was performed to determine the relationship that best models the acceleration profile. The most significant relationship was a power function as shown in Equation 1 below ($P < 0.0005$). The constant and coefficient for the average, 15th and 85th percentile acceleration are offered in table 3.

$$t = a_1 d^x$$

Equation 1: time-distance power function

Where t is the acceleration duration in seconds, a_1 is the constant, x is the coefficient and d is the distance in meters

Table 3. The constants and coefficients for the power function model to determine time from acceleration distance.

	a_1	x
Average	1.36	0.40
15^{th} percentile	1.78	0.34
85^{th} percentile	1.16	0.42

The Predicted and Actual curves were statistically similar ($P < 0.0005$). The models are appropriate for accelerations, where a vehicle travels more than a meter. However, when comparing the actual acceleration profile to the power function model, the results were statistically similar; the RMSE (root mean square error) was less than 0.07 seconds for the average and 85^{th} percentile models and 0.09 seconds for the 15^{th} percentile model.

By selecting 0.15 g as the (constant) normal acceleration [16] for a vehicle accelerating 15 m from a stop sign in a normal fashion, an investigator might calculate a time of 4.5 seconds; meanwhile, this research (test data and model) shows a realistic time of about 4.0 seconds for a distance of 15 m; the error in this scenario would be an overestimate of 13%.

Distance - Time Model

Figure 9 suggests that a quadratic function would best model the change in distance over time during acceleration. Equation 2 below is a quadratic function of the distance as a function of acceleration time. Table 4 specifies the quadratic coefficients a_1 and a_2 and the constant k.

$$d = a_1 t^2 - a_2 t + k$$

Equation 2: Distance-time quadratic function

Where d is the distance in meters and t is the acceleration duration, in seconds

Table 4. Distance-time quadratic equation coefficients and constant.

	a_1 (m/s^2)	a_2 (m/s)	k (m)
Average	**1.124**	**1.044**	**- 0.086**
15^{th} percentile	**1.029**	**1.725**	**0.546**
85^{th} percentile	**1.773**	**2.154**	**0.511**

Again, this model applies for acceleration durations between 1 to 5 seconds. For acceleration time greater than 5 seconds, the literature suggests that a linear decreasing acceleration would apply.

Figure 12 below outlines the distance-time relationship and models for acceleration duration of 1 to 5 seconds.

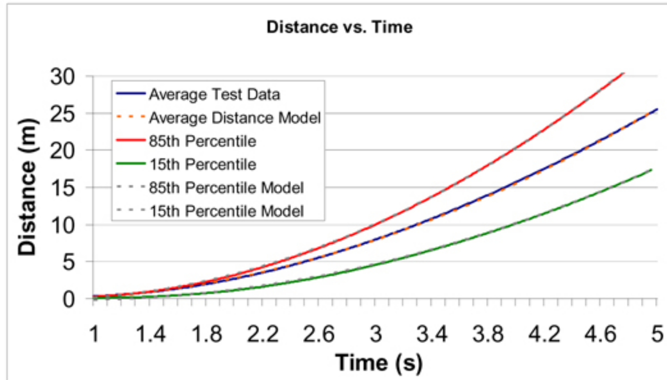

Figure 12. Distance versus time data and models.

Speed - Time Model

Figure 8 above suggests that acceleration was a three phase process, which would suggest that a cubic function would best model the change in speed over time in acceleration. Equation 3 below is a cubic function of the speed as a function of acceleration time. Table 5 specifies the cubic coefficients a_1, a_2 and a_3 and the constant k.

$$v = -a_1 t^3 - a_2 t^2 + a_3 t - k$$

Equation 3: Speed-time cubic function

Where v is the speed in meters per second and t is the acceleration duration, in seconds

Table 5. Speed-time cubic equation coefficients and constant.

	a_1 (m/s^4)	a_2 (m/s^3)	a_3 (m/s^2)	k (m/s)
Average	**0.013**	**0.043**	**3.014**	**2.174**
15^{th} percentile	**0.011**	**0.030**	**2.622**	**2.477**
85^{th} percentile	**0.018**	**0.136**	**3.953**	**2.269**

Figure 13 below outlines the speed-time relationship and models for acceleration duration of 1 to 5 seconds.

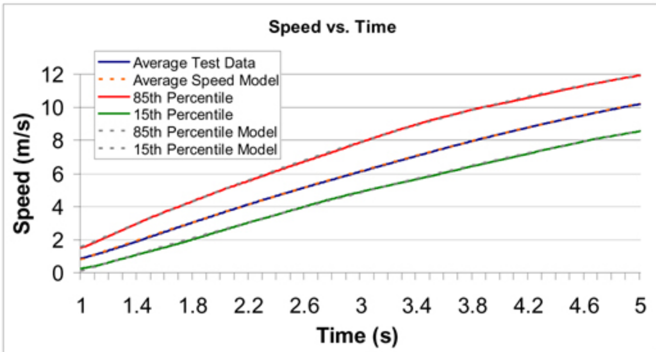

Figure 13. Vehicle speed during acceleration; test data and models; models are the dotted lines and the solid lines are the experimental test data.

Drivers Who Did Not Stop

Approximately one-quarter of the drivers did not stop before entering the intersection. This research does not specifically offer data or models to address the drivers who did not stop near the stop sign or stop line prior to entering the intersection. It is noteworthy however that contrary to the acceleration profile of those who stopped, the speed versus time graph in Figure 14 below shows that a constant acceleration assumption may be made.

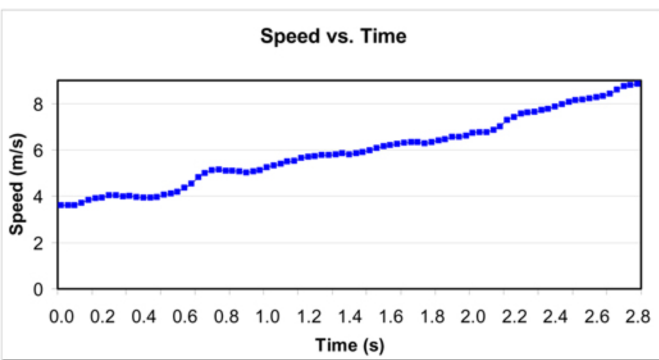

Figure 14. Speed graph for one sample at intersection #3, where the driver did not stop.

DISCUSSION

The average acceleration values from this research were consistent with results found by Fugger [10], but slightly higher and phase 1 occurred over a slightly shorter duration. Fugger measured accelerations at signalized intersections. This current research shows that accelerations at two-way-stop controlled intersections are likely higher than those at four-way-stop controlled intersections.

According to the data noted above, a (constant) acceleration of 0.15 g, commonly utilized and based on Fricke [16] would be classified as relatively slow for a vehicle accelerating from a stop sign area over a duration of 3 to 5 seconds. The results also show that an assumption of a constant acceleration will lead to underestimates of the duration of acceleration for short acceleration durations and overestimates of the duration of acceleration for longer acceleration durations.

The stopping position (or the location where the vehicle's speed was slowest) and the secondary acceleration phase are perhaps the most relevant to crash reconstruction experts in most cases. However the phases that are most relevant depend upon the type of case. If the car accelerated only 2.5 m before impact, then phase 1, the initial slow phase, is extremely important. If modeling from "stop line" or "road edge" and the vehicle started from a stop behind those landmarks, then phase 1 is of nearly no value. If the vehicle accelerated 30 m and reached its desired speed of 50 km/h, and the time and distance analysis is from the stopped position, then all three phases are significant and should be considered. Therefore the time of the acceleration is a function of the portion of the displacement accounted for.

$$t = \int_{\alpha}^{\Omega} f(s)$$

Equation 4: Time as a function of distance

Where t is the time, α is the start of the portion of the acceleration included in the analysis *Ω*, is the end of the acceleration included in the analysis and f(s) is a function of the distance traveled during the acceleration.

Yan [13] showed that acceleration decreases as the gap in traffic increases. This research did not specifically consider the effect of approaching traffic; however, approaching traffic was often present during the studies. Those utilizing this research should understand that drivers generally accelerate at a greater rate when there is approaching traffic than when no traffic is present. A way to best address the differences in acceleration due to traffic would be to utilize the 15^{th} percentile and the average acceleration equations if there is no traffic; and the average and the 85^{th} percentile equations if traffic is present. While future research may be able to differentiate the differences due to traffic, the results offered in this research show the acceleration of drivers to be relatively predictable regardless of traffic.

Our analysis did not focus on the third phase of the acceleration, which is when the acceleration reduces to zero (constant velocity) [3, 5, 7, 8]. The studies mentioned earlier have shown that acceleration is linearly decreasing once peak acceleration is attained. Hence, any acceleration occurring beyond the scope of this research could be extrapolated using a linear decreasing trend of 0.04 to 0.05 g per second [3, 5, 8].

The acceleration within two-way-stop sign controlled intersections was slightly higher than signal controlled intersections or all-way-stop controlled intersections; this was not unexpected. At a four-way or all-way-stop control intersection, there is not the urgency or conflicting traffic typical of a two-way-stop controlled intersection. In the context of this paper, urgency refers to the proximity of approaching traffic.

The distribution of the acceleration choice of the drivers was near-normally distributed. Vehicle acceleration capability has very little to do with the results in that only two drivers in the naturalistic study exceeded an average acceleration of 0.34 g over the initial 3 seconds of acceleration. As a comparison, in closed course testing [17], in the first four seconds of acceleration, a 1997 Chevrolet Lumina reached a speed of more than 13.4 m/s (30 mph) and a 2001 Honda Civic reached a speed of slightly more than 17.6 m/s (39 mph). These speeds are magnitudes greater than the rates seen by drivers in traffic.

One of the goals of the crash reconstruction is to determine the time available to the driver on the major road and to determine from that information, if the driver on the major road could have avoided the crash. On the basis of the acceleration distance, time to accelerate 10 m at a two-way-stop controlled intersection when accelerating from a stop is approximately 3.4 seconds. In another example, if a driver accelerated 6 seconds, the best way to model that acceleration would be to assume the Power function to a duration of 5 seconds and then utilize a linear decreasing model of 0.04 or 0.05 g/s during the remaining second (see Figure 7).

An example of how this research may be applied may be of assistance. Given a driver faced with a response to a minor street vehicle that does not stop for a stop signal (or stop sign) in daylight, the average perception-response time would be near 1.1 seconds [18]. Also assuming the major road driver needed another three seconds to slow enough to allow the intruding minor road vehicle to pass without incident. In this example, the point at which 50% of major road drivers would avoid this crash would be if the duration of the acceleration was 4.1 seconds. If the acceleration duration was longer, more would avoid and if the acceleration was shorter less would avoid this crash scenario (all things being equal). This research shows that it will take approximately four seconds to accelerate 15 m, which suggests that about 50% would avoid the crash scenario presented above. Additional analysis could also be performed using an 85th percentile driver's response for the given scenario or an 85th percentile acceleration using Monte Carlo type analysis to account for the distribution of each entry in the analysis. See the related paper by Bartlett [19]. Another example would be to check the impact speed calculations from momentum, energy methods and/or simulation results against the presented models to estimate the driver's acceleration.

From the results of this research, crash reconstructionists may also determine the likelihood that a driver stopped for a stop sign at a two-way-stop controlled intersection. If the calculated speed at impact is greater than the 85th percentile speed for the given acceleration distance, the probability is that the vehicle did not stop. The crash reconstructionist may compare the calculated impact speed with the average and 85th percentile speeds for the distance (stop line to impact). If the speed at impact is much greater than the speed of drivers for the given acceleration distance, the likelihood that the driver did not stop is greater. Furthermore, crash reconstructionists may utilize Figures 10,11,12,13,14 as evidence of the likelihood that a driver failed to stop. For instance, if a driver is traveling 10 m/s (22.4 mph) or greater after an acceleration distance of 11 m, it would be consistent with a driver who did not stop. Eighty-five percent of drivers who did stop would be traveling 9 m/s (20.3 mph) or less after 11 m. Further analysis may be done by comparing the average and 85th percentile speeds (15th percentile acceleration duration) with Equation 5 below.

$$85^{th}\text{ percentile} = \text{Mean} + \text{Standard deviation} \times \text{z-score}$$

Equation 5

The z-score for the 85th percentile in the equation above is 1.033

One of the ways this research may be utilized would be to compare the acceleration profile of drivers using Event Data Recorder (EDR) results with the manner in which drivers have accelerated in research. Such an example is provided below in Figure 15. The speed pattern during acceleration falls between the average and 85th percentile acceleration profiles of drivers in this research (See Figure 13). Therefore, one may conclude that this driver's acceleration was slightly above average for a two-way-stop controlled intersection when compared to the results from this research.

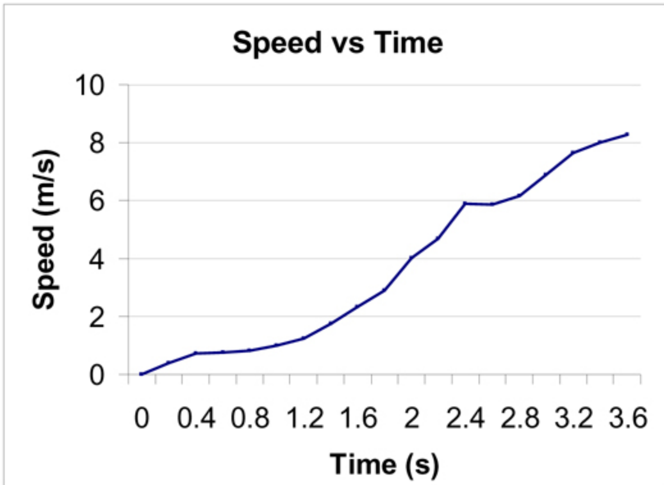

Figure 15. Speed vs. Time graph based on a download from a Ford vehicle that accelerated into a two-way-stop controlled intersection before being struck.

CONCLUSIONS

Time - distance, distance - time and speed - time models were presented for vehicle accelerations at two-way-stop sign controlled intersections. The models were based upon real world driver behavior. Much like Fugger [10], the naturalistic study portion of this research involved eleven specific intersections and 244 unaware drivers. Additionally, 10 drivers were tested in instrumented vehicles.

Drivers at two-way-stop controlled intersections exhibited three phase accelerations, an initial slow phase, presumably when the foot moves from the brake to the accelerator pedal and the vehicle responds to throttle input. A second phase starts near 0.9 seconds after the initiation of movement and involves a more aggressive acceleration in which the driver reaches a peak speed near 1.6 seconds after initiation of movement. The third phase of acceleration involves a linear decrease in acceleration until the driver reaches a constant speed. The average acceleration over the duration of a portion of acceleration is dependent upon the portions of the acceleration accounted for in the time and distance analysis.

The variance between drivers was relatively small and peak accelerations rarely reached the capabilities of the vehicle. Therefore, consistent with prior research [1], driver acceleration is a choice based upon the type of intersection (two-way versus four-way, versus arterial), rather than a factor that is based upon the capabilities of the vehicle.

Time-distance, distance-time, and speed-time equations were offered to model drivers' acceleration behavior at two-way-stop controlled intersections. Please also note that the data and models applies for acceleration time of one to five seconds at a two-way-stop controlled intersections. The investigator is urged to use judgment when applying these models for accelerations at intersections or scenarios that differ significantly from those utilized in this research.

LIMITATIONS AND FUTURE WORK

Further research may also yield information on the probable dependence of acceleration on other variables such as the effect of intersection geometry/topography, sight lines, presence of approaching/conflicting traffic, the speed limit, etc. This research expands upon that of Fugger and others [10, 11, 13, 14] who measured acceleration at four-way-stop controlled intersections with traffic signals. Future research of accelerations at arterial crossing and at on-ramps is also warranted.

Future research should be conducted to expand upon these findings and could include different vehicle types, different grades, different vehicle approach speeds and distances. The current research offers the average acceleration profile and the variance between drivers at eleven two-way-stop control intersections, as well as ten other drivers who were driving instrumented vehicles.

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