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ABSTRACT

This paper quantifies the deceleration of motor vehicles as they were routinely stopped for an expected hazard in a real world environment. It was observed that the deceleration rate varied non-linearly, with a peak value of about 0.25g as the vehicle decelerated through the speed range of 20 to 30 km/h. This deceleration pattern was common to all evaluated categories of passenger vehicles.

A mathematical model was developed to define the deceleration profile; enhancement of this model yielded predictive relations for the velocity, position and remaining braking time of decelerating passenger vehicles.

INTRODUCTION

Within the field of accident reconstruction, it is often advantageous to have the driving characteristics of typical vehicle operators quantified; this knowledge may form the foundation of a specific reconstruction case or assist in the technical interpretation of witness evidence. For traffic/roadway engineers, the knowledge of driver behavior is beneficial in the design of roadways and positioning of road signs.

Previous studies have addressed driver characteristics such as reaction time for unexpected roadway hazards [1, 2, 3, 4] and the effect of environmental factors on such reactions [5]. Other sources have proposed estimates of "normal" and "rapid" rates of motor vehicle acceleration [6, 7] (Note: the results presented in reference 7 are incorrect as a consequence of a fundamental procedure fault). While these studies have endeavored to quantify other driver parameters, the "typical" deceleration profile of vehicles during daily driving has not been adequately documented.

Prior to this study, only primitive information had been available which considers how typical operators decelerate their motor vehicles for routine and expected obstacles. Current literature often presents a constant rate of deceleration for "normal" braking with the maximum braking rate limited by the tire/roadway coefficient of friction.

Precise definition of a universal motor vehicle deceleration pattern is impossible as many factors influence each motorist's driving style; human factors, environmental factors and vehicular limitations all unquantifiably influence an individual vehicle's deceleration pattern. However, a more precise understanding of "typical" vehicular deceleration may be realized when sufficient real world data are considered.

The purpose of this paper is to quantify the deceleration trends of motor vehicles as they routinely stop for an expected obstacle (i.e. a stop sign). The source data for this study were unobtrusively collected in a real world environment and are considered reflective of unalerted vehicle operator characteristics. The deceleration patterns of differing motor vehicle classes were compared. A generalized deceleration model was developed and is proposed to be representative for passenger vehicles.

The data collected in this study also provide a comparative reference for the magnitude of acceleration/deceleration rates sustained by vehicles involved in sideswipe collisions and other frictional collisions that have few tangible analogies.

REVIEW OF LITERATURE

A literature search was conducted to ascertain what data are currently available that provide insight into the characteristics of routine motor vehicle deceleration. The search yielded numerous resources that quantify the maximum rate of vehicle deceleration as limited by tire friction for a variety of road surfaces and environmental conditions [8, 9, 10, 11, 12]. In addition, a series of publications address the braking characteristics of motor vehicles under "Emergency Braking" conditions [13, 14, 15]. However, these references do not present the rate of deceleration typically applied during routine braking.

Fricke [6] tabulates common acceleration and deceleration rates. This reference introduces a value of 0.20g for *"normal braking, no skidding,"* but does not develop this proposal further.

EXPERIMENTAL PROCEDURE

Decelerating vehicles were discretely monitored and their deceleration histories were recorded. The data collected from this research were then analyzed to establish trends and quantify the deceleration process.

EXPERIMENTAL APPARATUS – Speed data were acquired using a "Stalker" radar gun. The radar unit transmits a signal that disperses over the horizontal plane. The unit then evaluates the absolute speed of a target from the returned signal to a precision of 0.1 km/h by applying the Doppler principle. To improve the authenticity of the returning signal, the radar signal dispersion and return were collimated using an aluminum aperture. This reduced the potential for the returning signal to record extraneous reflections from background events; sources of extraneous data include secondary vehicles, pedestrians and weather related phenomena such as rain and wind blown leaves.

Proper operation of the radar gun was confirmed at the start of each test period by performing an internal hardware calibration; this process utilizes the unit's own internal electronics to verify functionality. A secondary calibration was performed using a calibrated tuning fork. No faults with the radar gun system were recorded.

The battery operated radar gun was interfaced to a portable computer and was sampled at a rate of 31.25 Hz. The acquisition of data from the radar gun unit was moderated by proprietary software. The raw data were stored for later analysis.

The portable radar acquisition system was concealed entirely within an unmarked vehicle (the "radar vehicle"), with the tinted windows of the vehicle obscuring the radar unit and its operators. Without any visual cue, the radar vehicle was indistinguishable from any typical parked vehicle.

TEST LOCATION AND ENVIRONMENT – Deceleration testing was conducted between September 1995 and January 1998 at various locations within the city of Surrey (a suburb of Vancouver), British Columbia, Canada. The data was collected under varying weather conditions (rain, wind, and clear), road surface conditions (wet and dry) and illumination conditions (daylight, dusk and after nightfall). Test sites were chosen that were straight and level on the approach to a stop sign; therefore, there was an unobstructed view of the signage.

Stop sign controlled intersections were preferentially chosen, based upon geometric and traffic volume constraints. Streets with multiple lanes in each direction and intersections with active cross traffic were rejected as unsuitable since they permit excessive background traffic to generate extraneous radar data. As the acquisition of deceleration data from one vehicle in isolation was desired, testing locations with high traffic volume were also unsuitable because secondary vehicles tended to enter the radar gun's field of view before the primary vehicle completed its deceleration.

TEST PROCEDURE – The radar vehicle was driven to a selected site and parked as close to the edge of the roadway as practicable. The radar vehicle was positioned facing the intersection stop sign in the same direction as the target vehicles. The radar unit was mounted in the radar vehicle on a tripod and aimed forward to be approximately parallel to the roadway. The calibration of the radar gun and the functionality of the control software were verified prior to the commencement of testing.

During testing, target vehicles were identified as they approached and passed the radar vehicle from behind. After the subject passed the radar vehicle, the radar system recorded the speed of the decelerating target vehicle as it approached the stop sign.

Operation of the radar system required two persons. One person was responsible for operating the radar monitoring system and pre-processing the acquired data; this pre-processing included truncating the data set or rejecting the run if it was unusable. The otherwise unconditioned data were saved for later processing. The second person observed the approaching vehicles and ascertained when a suitable vehicle target was approaching. A target was selected if it was sufficiently separated from other vehicles that it could be independently tracked. The secondary role of the observer was to identify the make, model and approximate model year of each recorded vehicle and classify it into one of the following categories: passenger automobiles, minivans, pickup trucks/sport utility vehicles (SUVs), tractor/trailers, sports cars, buses, vans and commercial trucks. Sport utility vehicles are categorized with pick-up trucks as they are built on similar platforms and have similar performance specifications. The "sports car" category reflects vehicles that are marketed for their performance: Ford Mustang, Chevrolet Camaro, Dodge Viper, Toyota MR2, Mazda RX7, etc.

DATA COLLECTED – Upon acquisition, a plot of a vehicle's deceleration history was immediately generated on the portable computer (see Appendix A for a sample raw data plot); the quality of the data and the usable duration of the recorded event were assessed from this plot. Data runs were immediately rejected if the data was fatally contaminated by extraneous data, if the usable sampling duration was inadequate, or if the subject vehicle behaved uncharacteristically. Examples of uncharacteristic behavior include those vehicles that did not appreciably decelerate for the stop sign (i.e. did not attempt to stop), and those vehicles that were initially traveling at speeds that were abnormally distant from the municipal speed limit of 50 km/h.

Deceleration data were recorded for a total of 313 vehicles. The vehicles were classified into motor vehicle type based upon the make, model and estimated vintage. The occurrences of each type of vehicle are summarized in Table 1.

Table 1. Vehicle Type and Frequency

Vehicle Type	Number of Recorded Decelerations
Passenger Automobile	153
Pickup Truck/SUV	61
Minivan	45
Sports car	17
Van	17
Commercial Truck	09
Tractor/Trailer	06
Bus	05
Total	313

The volume of data collected for the "Passenger Automobile," "Pickup Truck/SUV," and "Minivan" categories was adequate to permit further analysis. The remaining categories contained insufficient entries to be statistically significant, and are not further considered within this paper.

CONDITIONING OF RAW DATA

REMOVAL OF EXTRANEOUS DATA – The deceleration history data for the "Passenger Automobile," "Pickup Truck/SUV," and "Minivan" categories were processed manually as the data were not always conducive to automated processing. The experimental procedure generally isolated the target vehicle from most other sources of radar distraction; the acquired data plots typically indicated that a very pure signal had been returned from the intended target. However, two easily removable types of extraneous data were recognized.

In those cases where a secondary vehicle entered the field of the radar prior to the completion of the data collection, two concurrent acceleration/deceleration curves were recorded. This auxiliary vehicle may have been a vehicle following the target, a distant vehicle ahead of the target, or an automobile approaching the target from the opposing direction. These secondary vehicle traces were readily apparent when the raw data was plotted in the Speed vs. Time domain. The artifacts from the secondary vehicle were removed and the gaps in the raw deceleration were linearly spliced. Figure 1 illustrates this category of extraneous data.

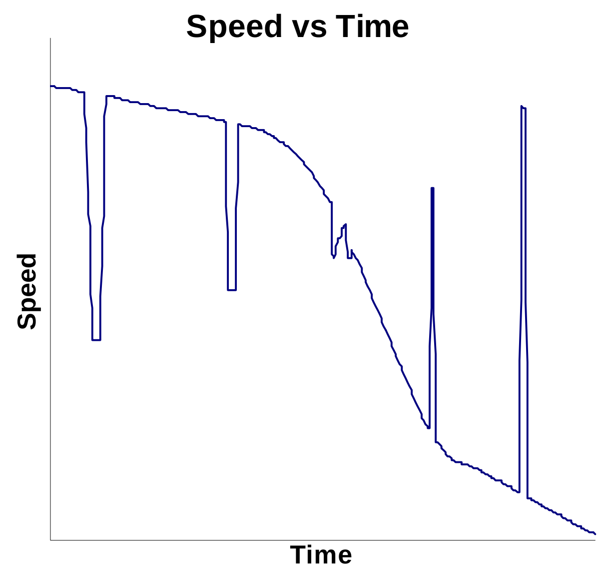

Figure 1. Artifacts of a Secondary Vehicle As Extraneous Data

A second category of extraneous data emerged when insufficient signal was returned from the target. The radar gun then either recorded a null value indicating that no meaningful signal was returned, or registered the speeds of background objects and events. Within the saved runs, these distractions were typically transient and bounded by solid data on either side. These unwanted points were manually deleted and the resulting gap in the target vehicle data was bridged as a linear fit. This category of extraneous data is illustrated in Figure 2.

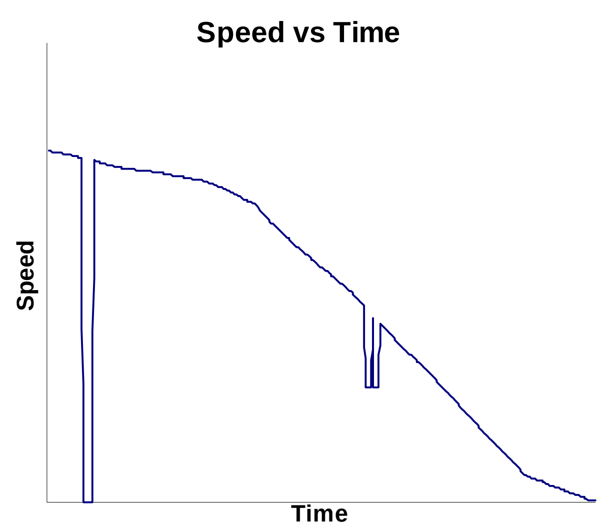

Figure 2. Extraneous Data from Loss of Signal and Background Events

A total of 46 runs were discarded because the deceleration record contained sufficient extraneous readings that the deceleration profile could not be confidently resolved.

FILTERING OF PROCESSED DATA – Sampled radar data inherently contain random noise superimposed on the "true" values. The magnitude of the noise within the recorded radar data was minimal. However, subsequent analysis required the differentiation of the speed data with respect to time to evaluate instantaneous deceleration rates. As piecewise differentiation (i.e. the differentiation of adjacent values over the corresponding time interval) amplifies the influence of high frequency oscillations (typical of random noise), it was necessary to lightly filter the raw data.

The raw speed data were smoothed by calculating the average of the considered point and three adjacent lower and higher values to yield a "filtered speed" value; this seven sample window represents 0.224 seconds of recorded data. The instantaneous deceleration rate was calculated from the "filtered speed" data by the piecewise differentiation of adjacent data points. The instantaneous deceleration rate was then smoothed to yield a "filtered deceleration" rate by averaging over a window of seven raw deceleration samples, as for the speed data. Thus, this layered filtering technique derived each filtered deceleration value from a total of 13 raw speed readings (corresponding to 0.416 seconds of sampled data); this filtering preferentially weighted the proximal raw speed samples, while distal values were less influential. This process yielded filtered speed data that were strictly decreasing over the considered range; only positive deceleration values were recorded. Figure 3 diagrams this filtering process.

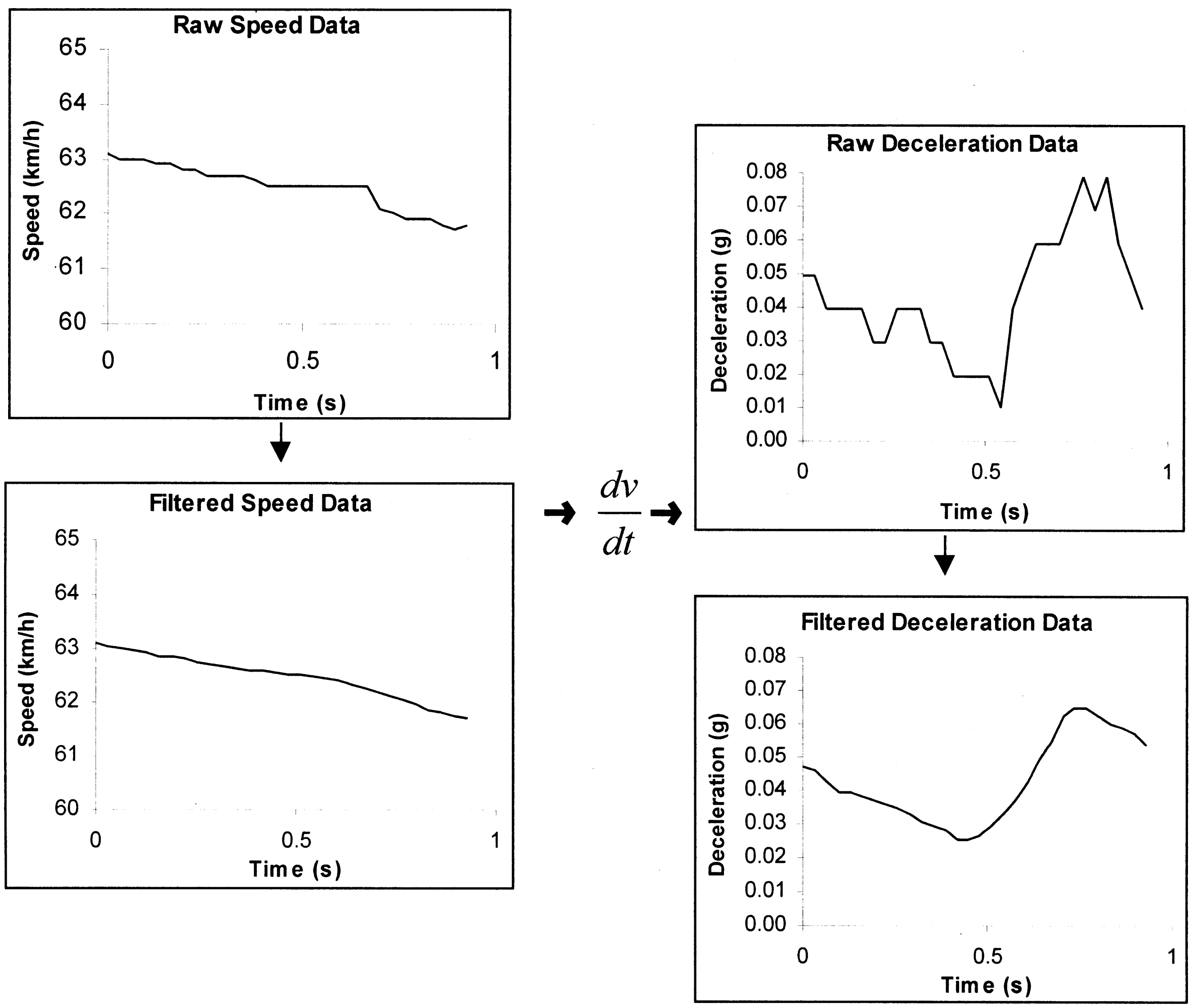

Figure 3. Representation of Filtering Process

EVALUATION OF CONDITIONED DATA

Performance trends were established for the “Passenger Automobile,” “Pickup Truck/SUV,” and “Minivan” data. These profiles were then mathematically quantified to define “typical” vehicle deceleration.

DECELERATION MODEL – The deceleration plots of each vehicle were compared, and a definitive pattern recurred. The data suggest that the rate of vehicle braking may be divided into three phases. During the “Initiation Phase”, constant speed motion ends and braking is smoothly initiated. The “Active Braking Phase” considers the period where brake application is developed and the dominant amount of speed is dissipated. Finally, the deceleration rate is reduced to smoothly approach the target speed during the “Completion Phase”. Although these trends may be deciphered directly from the raw data, the three phases are most apparent in the plot of Speed vs. Time. Figure 4 illustrates these three phases.

It should be noted that distinct phases may not be readily apparent in those cases where a gradual transition between phases occurs. Consequently, subjective input was sometimes required to define the phase boundaries.

The deceleration history of each recorded vehicle was divided into the initiation, active braking and completion phases, where applicable. Each of the three phases of deceleration were independently assessed.

The Initiation Phase – The initiation phase represents the transition from constant speed motion to controlled braking. Typically, the initiation phase required approximately 3 seconds to complete, over which 7 km/h was dissipated at an average rate of approximately 0.064 g. As the initial speed of each vehicle was variable, the corresponding travel distance also varied. However, the approximate 3 second duration and 7 km/h speed loss was common to initial vehicle speeds from 40 to 70 km/h.

A small percentage of vehicle operators coasted their vehicles for a significant distance prior to initiating braking. This period of coasting was not included as part of the braking process.

The Active Braking Phase – The deceleration history of each vehicle in the active braking phase was divided into speed increments and the average deceleration rate was calculated for each increment. This result may be interpreted to indicate the average deceleration rate for a typical vehicle as it is braked through a specific speed range. The average deceleration rate through each speed increment was evaluated for each classification of vehicle; median values are presented in Table 2.

Table 2. Average Automobile Deceleration Data for the Active Braking Phase

Speed Range [km/h]	Passenger Automobiles	Pickup Trucks/SUVs	Minivans	Composite Profile
	Average Deceleration [g]	Average Deceleration [g]	Average Deceleration [g]	Average Deceleration [g]
0-10	0.215	0.156	0.153	0.181
10-20	0.254	0.232	0.199	0.237
20-25	0.271	0.246	0.233	0.257
25-30	0.262	0.256	0.226	0.253
30-35	0.238	0.236	0.208	0.231
35-40	0.212	0.202	0.186	0.204
40-45	0.192	0.187	0.154	0.182
45-50	0.173	0.171	0.150	0.168
50-55	0.172	0.178	0.139	0.168
Average	0.229	0.213	0.191	0.216

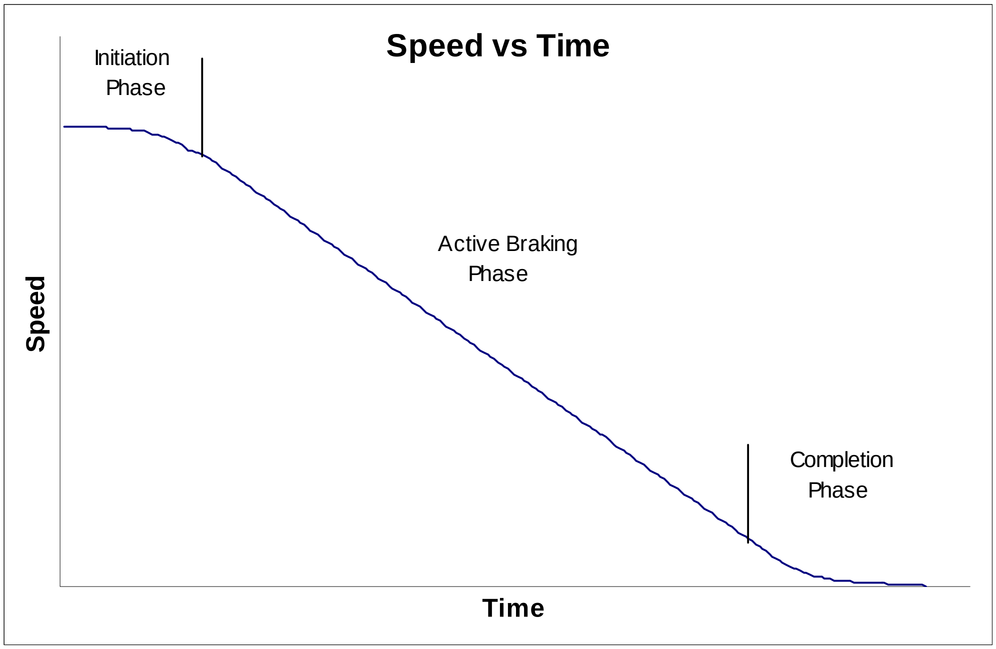

Figure 4. The Three Phase Deceleration Process

When the median deceleration rate for each speed increment was plotted, several trends emerged. The most dominant trend was that the deceleration rate varied non-linearly and maximized through the 20 to 30 km/h range. It may be inferred from this data that vehicle operators gradually increase brake application (i.e. increase the deceleration rate) as they decelerate, but eventually begin reducing brake application as their target speed approaches. The second notable parallelism is that this deceleration pattern was common to all three considered categories of motor vehicles: passenger automobiles, pickup trucks (including sport utility vehicles) and mini-vans. The deceleration profile for each category peaked over a similar range and exhibited comparable plot profiles. A composite curve incorporating data from these three motor vehicle designations was also prepared. These plots of deceleration history during the active braking phase are illustrated in Figure 5.

The composite deceleration profile illustrated in Figure 5 may be mathematically modeled by a variety of methods. Polynomial fits were considered, with higher order models achieving increasing degrees of correlation. Polynomial terms above the fifth order achieved a negligible improvement in accuracy. Alternate models were considered, including a bilinear fit. It was noted that a bilinear fit approximated the composite profile with sufficient accuracy that the added complexity of applying higher order polynomials was unwarranted. The composite data for the active braking phase may be modeled as follows:

5^{th} order polynomial*:

$$a = -1\times10^{-8}V^5 + 1.6\times10^{-6}V^4 - 9.6\times10^{-5}V^3 + 2.2\times10^{-3}V^2 - 1.6\times10^{-2}V + 0.22$$
$$\text{for } 3.4 < V < 55 \text{ km/h}$$

$$\text{where } V = \text{speed [km/h]}$$
$$a = \text{deceleration [g]}$$

Bilinear fit*:

$$a = 0.0036V + 0.175$$
$$\text{for } 3.4 < V < 22.5 \text{ km/h}$$

$$a = -0.0033V + 0.330$$
$$\text{for } 22.5 < V < 55$$

$$\text{where } V = \text{speed [km/h]}$$
$$a = \text{deceleration [g]}$$

The 5^{th} order polynomial and bilinear fit representations are compared to the composite data profile in Figure 6.

* These results are presented in imperial units in Appendix B.

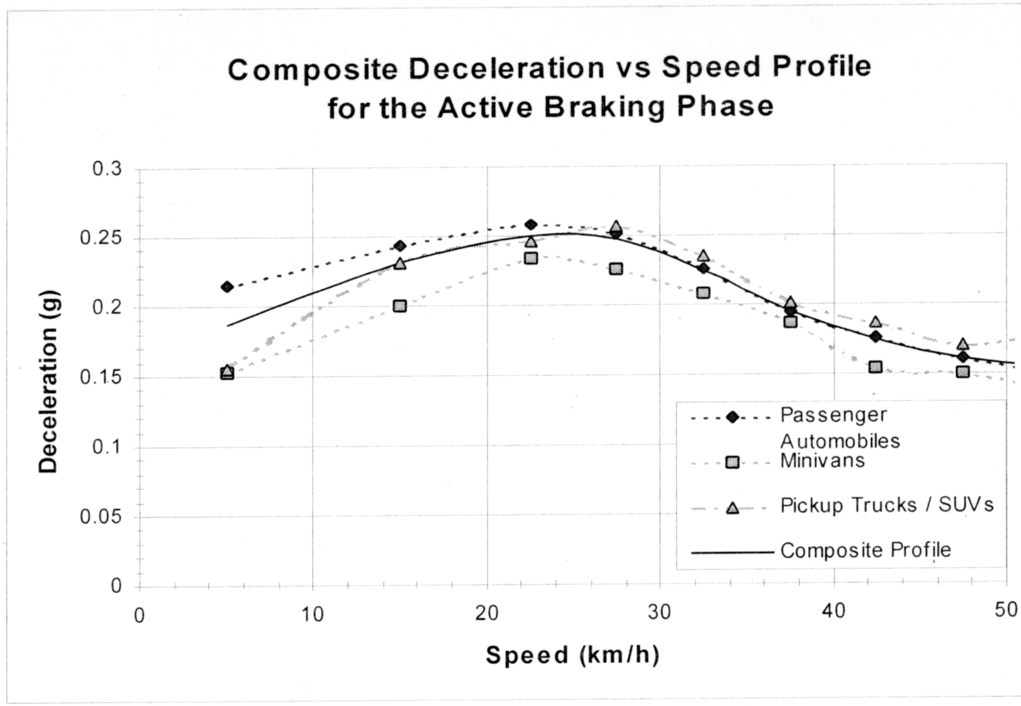

Figure 5. Deceleration vs. Speed Data for Passenger Automobiles, Minivans and Pick-up/SUVs. The composite profile includes the data from these three categories.

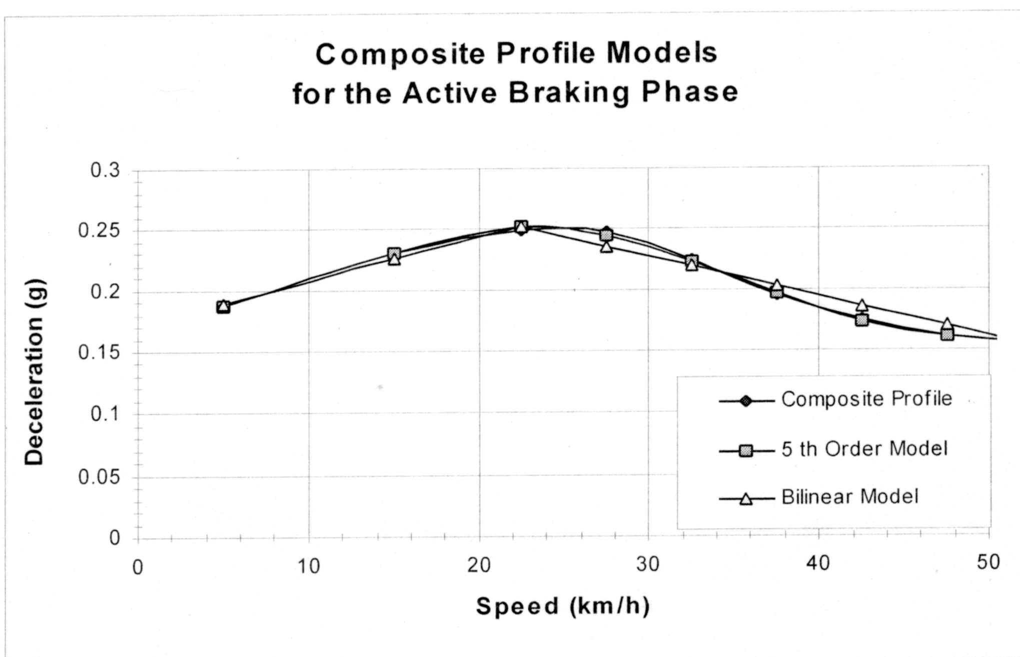

Figure 6. Mathematical Representation of Empirical Data for the Active Braking Phase.

The Completion Phase – The completion phase is the transition from the active braking phase to a stop; this transition mirrors the initiation phase. This phase typically occurs over approximately 1.7 seconds as the vehicle dissipates its final 3.4 km/h. This process typically corresponds to a traveled distance of about 1.6 meters.

Applicability of Braking Model – The three considered categories of motor vehicles collectively represent the majority of all non-commercial vehicular traffic. As these motor vehicle types exhibited common deceleration profiles, it may be inferred that these data may be applied to all non-commercial vehicular traffic. In a more general sense, deceleration for a stop sign is one of a set of expected events that emerge during routine driving. A clearly visible stop sign neither presents an unexpected hazard nor does it present a transient situation which commands complex operator reaction. Consequently, these deceleration profiles are considered to be representative of controlled vehicle deceleration for known hazards.

It should be recognized that the deceleration of any vehicle is defined exclusively by its operator. The collected data suggest that the variation among the deceleration profiles is more attributable to differing driving styles than environmental factors. Secondly, all of the research data were collected in an urban area with a municipal speed limit of 50 km/h. It is not known whether the driving characteristics of urban and rural vehicle operators are identical. Furthermore, the scope of this project does not include the assessment of deceleration profiles for vehicles traveling at speeds dramatically in excess of 50 km/h. Consequently, the braking model incorporating the composite deceleration profile is intended to establish a general pattern for vehicles decelerating from initial speeds of up to about 60 km/h.

SPEED/TIME/POSITION RELATIONSHIPS – Further development of the expressions for the three phases of deceleration yields relationships between the speed, deceleration rate, remaining braking distance and remaining braking time.

Actively Braking Vehicles – Definition of the three phase braking process permits evaluation of the position and speed of a vehicle at any instant in its deceleration. One application of this model is the assessment of the motion of a vehicle that is already actively braking; the considered vehicle would have already completed the initiation phase and would be decelerating in the active braking regime. The remaining braking time, distance and speed required to stop the vehicle is defined by the requirements to complete the active braking phase plus the time, speed change and distance dissipated during the completion phase. Mathematical development of the composite bilinear model yields these requirements; the resulting equations are combined with the completion phase values to yield the relations expressed in Table 3. Consequently, the expressions presented in Table 3 describe the speed, deceleration distance and/or time required for an actively braking vehicle to complete its deceleration. Speed vs. Time and Position vs. Speed plots (Figures 7 and 8, respectively) emerge from application of the Table 3 equations. Speed, deceleration and time values may also be graphically evaluated from these charts.

Table 3. Remaining Stopping Requirements for Actively Braking Vehicles

	Speed of Actively Braking Vehicle at Point of Consideration	
	3.4 < V < 22.5 km/h	22.5 < V < 52.5 km/h
Remaining Stopping Distance d [m]	$d = \frac{V^2 - 3.4^2}{44.8 + 0.46V} + 1.6$	$d = \frac{V^2 - 22.5^2}{73.5 + -0.42V} + 10.6$
Remaining Stopping Time t [s]	$t = \frac{V - 3.4}{6.2 + 0.064V} + 1.7$	$t = \frac{V - 22.5}{10.2 - 0.058V} + 4.1$
	Distance of Actively Braking Vehicle From Intended Stop Position	
	1.6 < d < 10.6 m	10.6 < d< 54.3 m
Speed at Indicated Position V [km/h]	$V = (0.23d - 0.368) + \sqrt{0.053d^2 + 44.63d - 60.24}$	$V = (2.25 - 0.21d) + \sqrt{0.045d^2 + 72.56d - 267.6}$

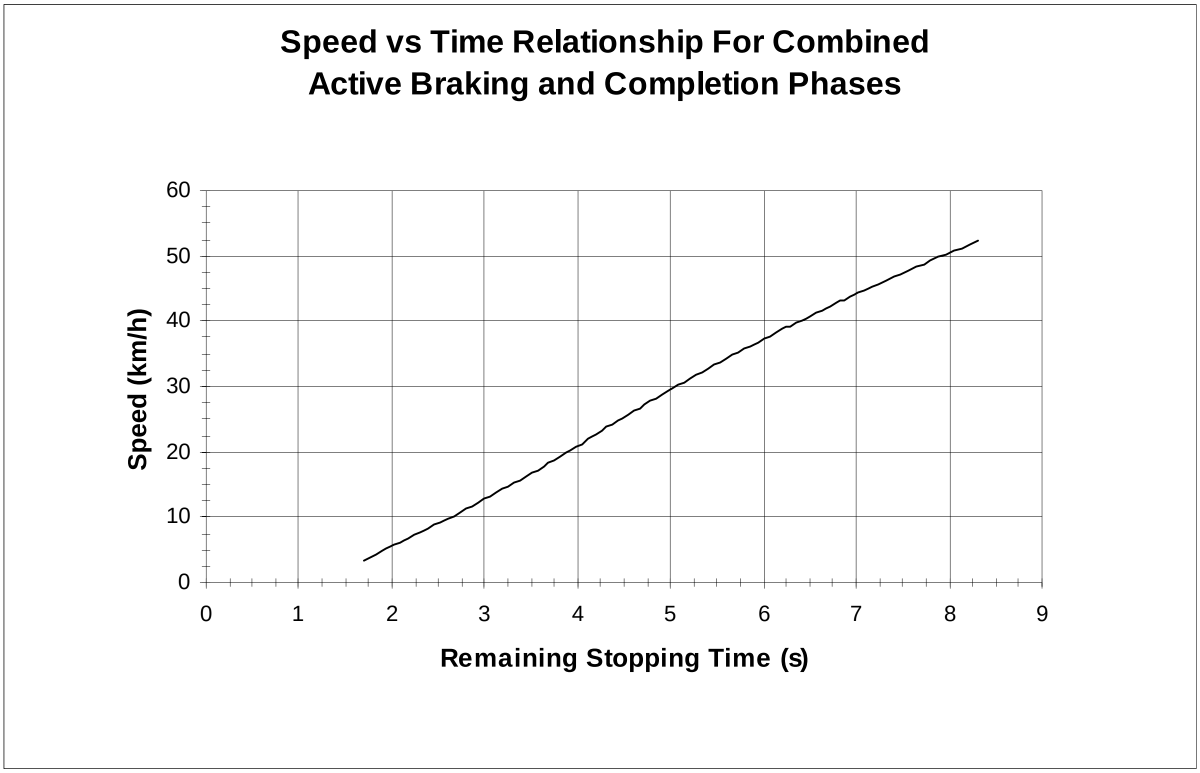

Figure 7. Speed/Time Relationship for Actively Braking Vehicles Decelerating to a Stop.

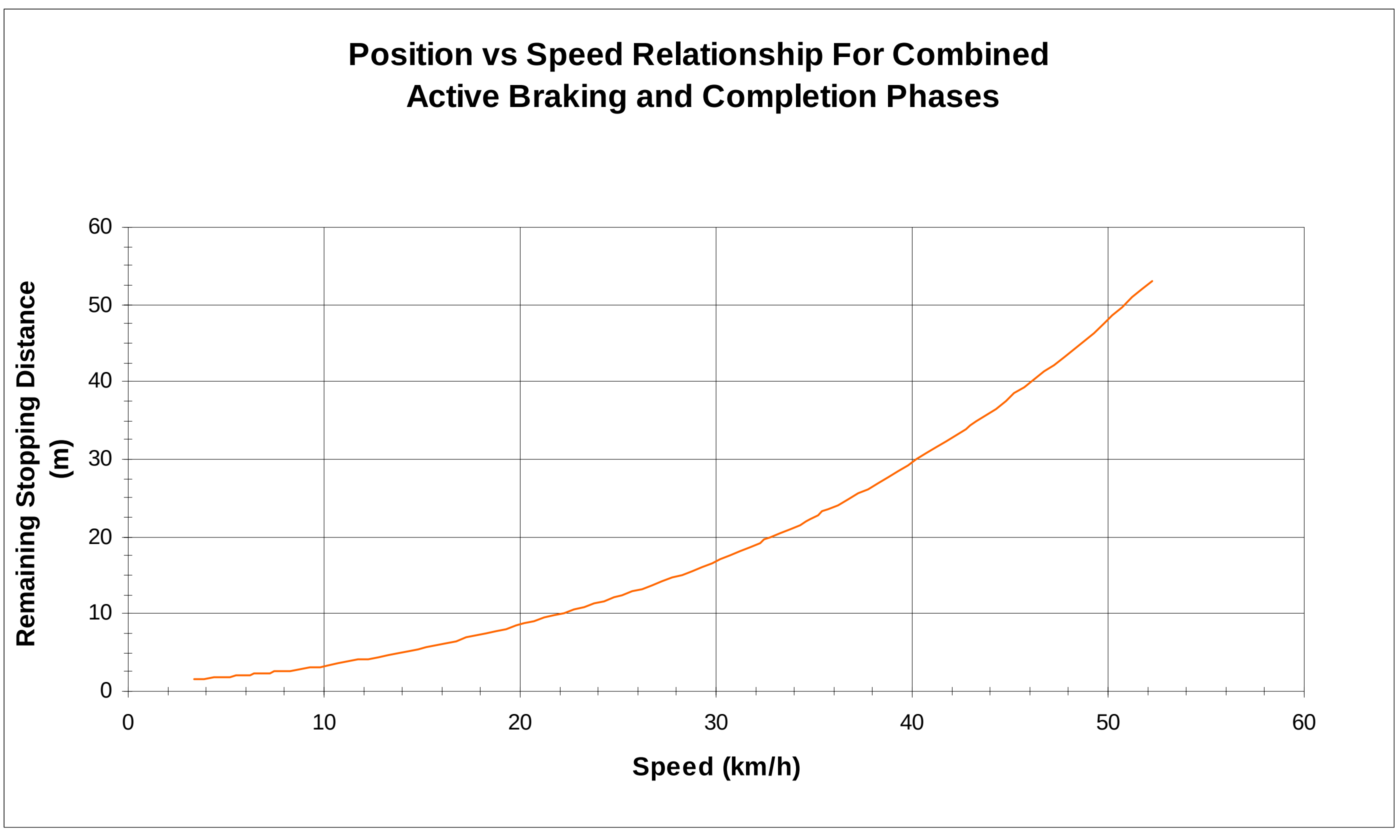

Figure 8. Position/Speed Relationship for Actively Braking Vehicles Decelerating to a Stop.

Table 4. Complete Vehicle Stopping Process

	Initial Pre-Braking Speed: 10.4 < V < 29.5 km/h	Initial Pre-Braking Speed: 29.5 < V < 59.5 km/h
Total Stopping Distance d [m]	$d = \frac{V^2 + 15.13V - 14.88}{0.3296V + 29.79}$	$d = \frac{V^2 + 76.00V + 193.6}{119.7 - 0.657V}$
Total Stopping Distancet t[s]	$t = \frac{V - 10.4}{5.75 + 0.064V} + 4.8$	$t = \frac{V - 29.5}{10.6 - 0.058V} + 7.2$
	Available Stopping Distance: 7.5 < d < 33 m	Available Stopping Distance: 33 < d< 111 m
Initial Pre-Braking Speed V [km/h]	$V = (0.16d - 7.53) + \sqrt{0.027d^2 + 27.23d + 71.7}$	$V = -(0.33d + 37.17) + \sqrt{0.11d^2 + 142.7d + 1242}$

The Complete Stopping Process – Calculation of a vehicle's pre-braking speed or the total distance and time required to stop a vehicle from a specific pre-braking speed necessitates consideration of all three phases. Table 4 presents bilinear model equations for the complete deceleration process. Figures 9 and 10 present these data in graphical form.

COMPARISON TO PUBLISHED DATA

Fricke tabulated a deceleration rate of 0.20g for *"normal braking, no skidding."* This constant deceleration may be compared to the mathematical models developed from this study. This study recorded an average deceleration rate of 0.216g during the active braking phase; this value is comparable to the referenced 0.20g rate.

However, this study also recognized motor vehicle deceleration as a three phase process. The average deceleration rates during the initiation and completion phases were noted to be significantly less than 0.20g. Thus, an out of context application of Fricke's constant deceleration rate to the two transition phases of the braking process would have the potential to introduce significant calculation error.

In summary, this study supports Fricke's 0.20g deceleration rate as being representative of the deceleration rate present during fully developed automobile braking. However, it is also necessary to consider the initiation and completion phases separately when assessing the vehicular motion. The use of a constant deceleration value to model the complete deceleration process is not recommended and may yield significant error.

APPLICATION OF RESULTS

Three potential applications of these obtained results within the field of accident reconstruction are proposed.

EVALUATION OF SPEED AT A GIVEN POSITION – The speed of a braking vehicle at a given distance in advance of an intended stopping point may be estimated. For example, the speed and remaining stopping time may be predicted for a normally braking vehicle 30 meters prior to stop. Since this distance falls within the active braking phase, the speed and remaining time at this point may be calculated directly from the bilinear model expressions in Table 3 or graphically from Figures 7 and 8. These relations estimate the speed of the vehicle as about 40 km/h with 6.4 seconds of braking remaining.

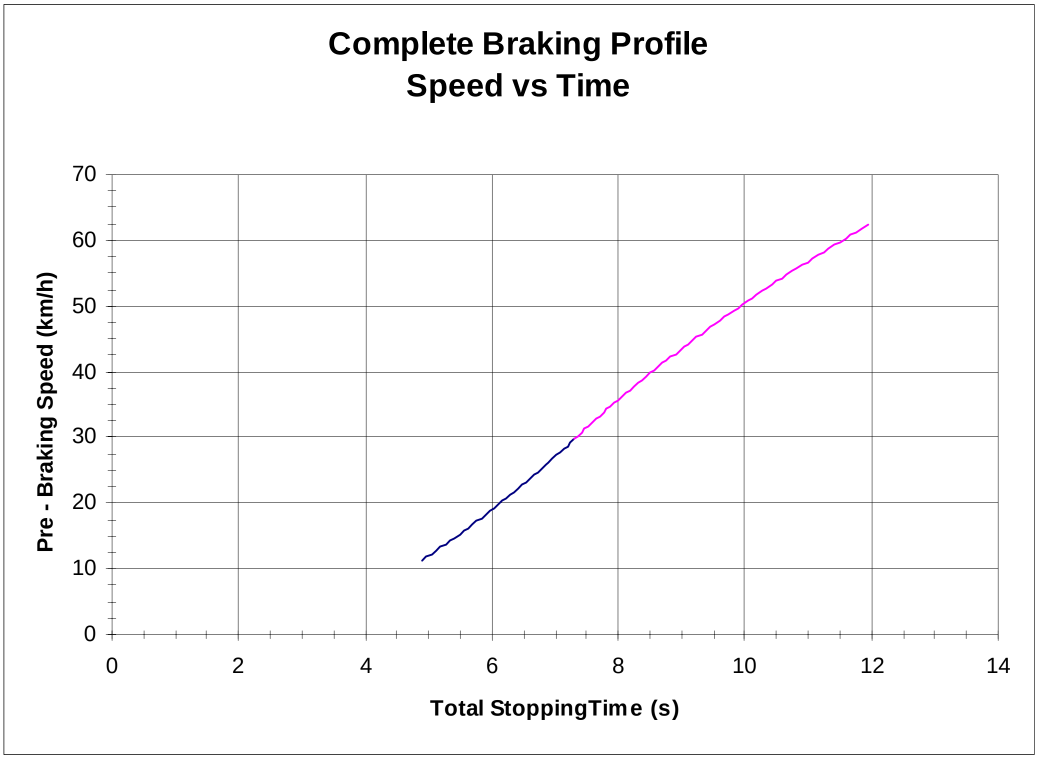

Figure 9. Speed/Time Relationship for the Complete Stopping Process.

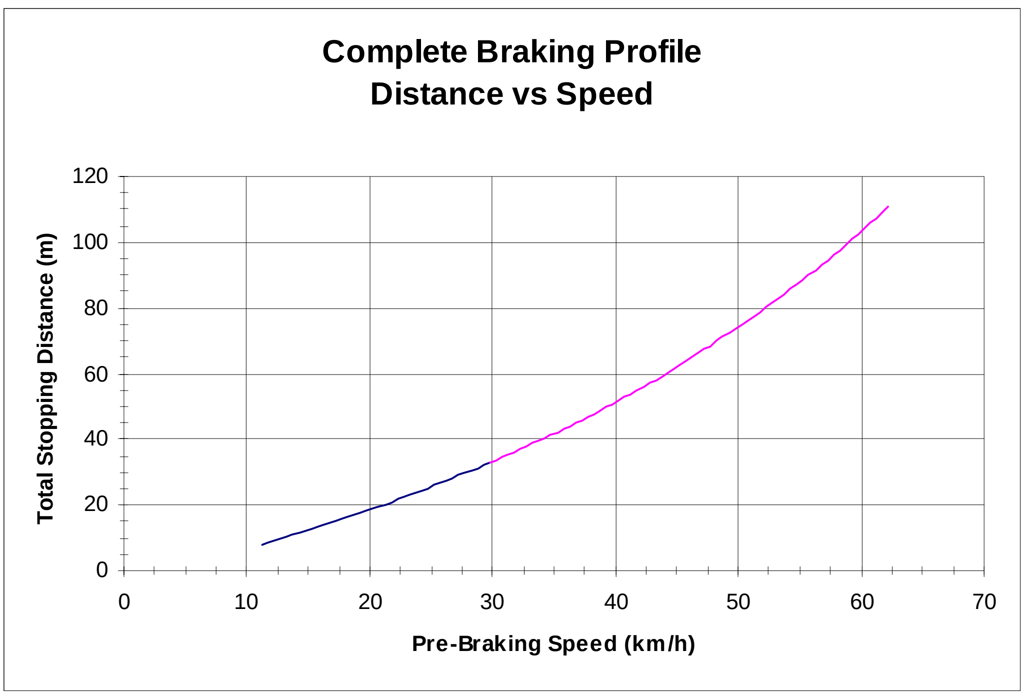

Figure 10. Position/Speed Relationship for the Complete Stopping Process.

STOPPING TIME AND DISTANCE EVALUATION – Evaluation of the time and distance required to stop from a given speed may be performed by adding the time and distances for each of the three phases. This may be directly assessed from the relationships presented in Table 4, or may be graphically assessed from Figures 9 and 10. For example, consider deceleration from an initial speed of 50 km/h. The Table 4 relations yield that a total of 9.8 seconds would elapse as a vehicle decelerates from 50 km/h to a stop in a total traveled distance of 74.8 meters.

COMPARATIVE REFERENCE – A third application for these results is as a comparative reference for vehicle decelerations to which vehicle operators routinely and voluntarily expose themselves. This study determined that operators typically decelerate their vehicles at a peak rate of about 0.25 g during routine braking for a known hazard such as a stop sign. The magnitude of the acceleration/deceleration rate present during some sideswipe automobile collisions may be compared to the magnitude of these decelerations. While it is cautioned that the acceleration acting during sideswipe collisions is a vector quantity, this paper may provide a practical benchmark when describing the acceleration magnitude of sliding contact collisions.

CONCLUSIONS

The results of this study are derived from empirical data that were collected in a real world environment from unalerted vehicle operators. Although the recorded vehicular deceleration histories were initially classified by categories of motor vehicle, the median deceleration profiles were noted to be comparable for each of the considered vehicle classifications. A composite deceleration profile was compiled and is considered to be representative for non-commercial motor vehicles during routine deceleration for a stop sign. Consequently, this deceleration profile is considered to be representative for controlled passenger vehicle deceleration for known hazards.

From the obtained data, it was recognized that vehicular deceleration is a three phase process. In the initiation phase, the vehicle operator initiates braking as a smooth transition from constant speed travel. An active braking phase follows as the maximum deceleration rates are achieved. Finally, a completion phase completes the process as the braking rate is reduced so that the vehicle smoothly comes to a stop. The two transition regions were defined in terms of the typical time and speed change required to complete these processes. A bilinear model of the active braking phase was developed; this model is considered sufficiently accurate to not warrant pursuing higher order polynomial equations.

Mathematical development of the bilinear model yielded expressions which relate the time, speed, distance and deceleration rate throughout the stopping process; from these relations, each value may be determined at a specific position or instant. The total distance typically traveled during deceleration from a specific speed is also calculable.

This study determined that operators typically decelerate their vehicles at a rate of up to about 0.25g during routine braking for a known hazard such as a stop sign. This provides a useful comparison for quantifying the magnitude of vehicular deceleration during sideswipe and other frictional collisions.

ACKNOWLEDGMENT

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RECOMMENDATIONS

This paper has quantified the deceleration profile of passenger vehicles stopping for an expected hazard from data collected in an urban environment. Future research to expand this model to consider higher pre-braking speeds would be beneficial as such work has not been previously presented. Furthermore, research to compare the deceleration profiles between urban and rural environments would be insightful about factors that influence operator driving characteristics.

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APPENDIX A: PLOT OF RAW DATA

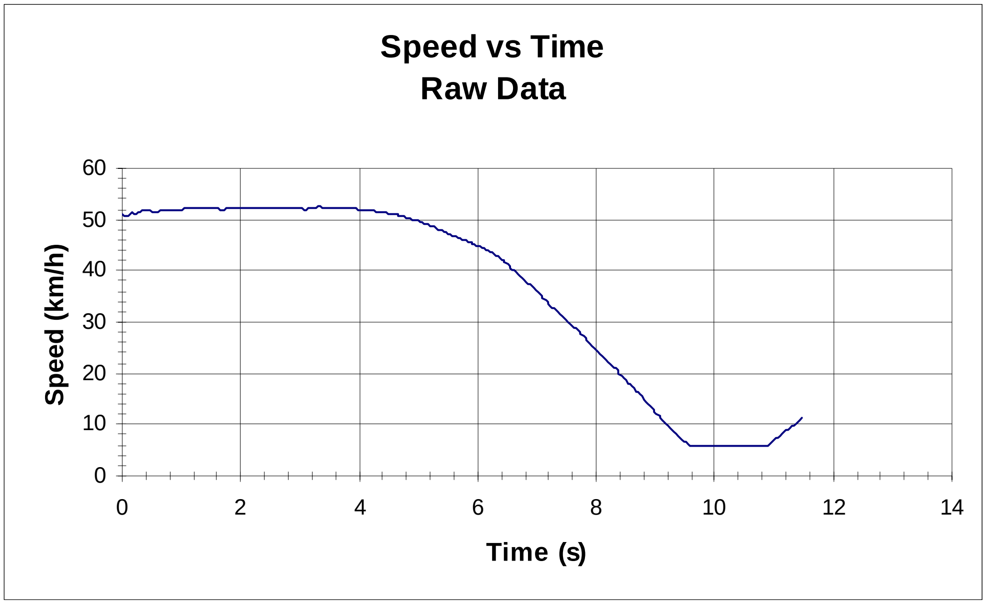

Figure A1. Plot of the Unfiltered Speed/Time Deceleration Profile of a Vehicle that did not Come to a Complete Stop.

APPENDIX B: ANALYSIS RESULTS IN IMPERIAL UNITS

The findings of this study may also be expressed in imperial units. The following key mathematical expressions and figures are presented in terms of imperial units for distance (feet) and speed (miles per hour).

The composite deceleration profile (illustrated in Figure 5) for the active braking phase may be modeled as follows:

5th order polynomial*:

$$
\begin{aligned}
a = &-1.1\times10^{-7}V^5 + 1.7\times10^{-5}V^4 - 4.0\times10^{-4}V^3 \\
&+ 2.2\times10^{-3}V^2 - 2.6\times10^{-2}V + 0.22 \\
&\text{for } 2.1 < V < 34 \text{ mph} \\
&\text{where } V = \text{speed [mph]} \\
&\qquad\quad a = \text{deceleration [g]}
\end{aligned}
$$

Bilinear fit*:

$$
\begin{aligned}
a &= 0.0058V + 0.175 \\
&\text{for } 2.1 < V < 14 \text{ mph}
\end{aligned}
$$

$$
\begin{aligned}
a &= -0.0053V + 0.330 \\
&\text{for } 14 < V < 34 \text{ mph} \\
&\text{where } V = \text{speed [mph]} \\
&\qquad\quad a = \text{deceleration [g]}
\end{aligned}
$$

Table B3 is presented as the imperial equivalent of Table 3. The expressions presented in Table B3 define the speed, deceleration distance and time required for an actively braking vehicle to complete its deceleration.

Table B3 — Bilinear Model Equations

	Speed of Actively Braking Vehicle at Point of Consideration	
	2.1 <V < 14 mph	14 < V < 32.8 mph
Remaining Stopping Distance d [ft]	$d = \dfrac{V^2 - 2.1^2}{0.088V + 5.27} + 5.3$	$d = \dfrac{V^2 - 14.0^2}{-0.079V + 8.68} + 34.8$
Remaining Stopping Time t [s]	$t = \dfrac{V - 2.1}{6.4\times10^{-2}V + 3.9} + 1.7$	$t = \dfrac{V - 14.0}{-5.8\times10^{-2}V + 6.3} + 4.2$
	Distance of Actively Braking Vehicle from Intended Stopping Position	
	5.2 <d < 34.8 ft	34.8 < d< 178 ft
Speed at Indicated Position V [mph]	$V = 0.044d - 0.33 + \sqrt{0.002d^2 + 5.321d - 23.42}$	$V = -(0.040d - 141) + \sqrt{0.0016d^2 + 8.64d - 104.5}$

Speed vs. Time and Position vs. Speed plots (Figures B7 and B8, respectively) emerge from application of the Table B3 equations for actively braking vehicles. Speed, deceleration and time values may also be graphically evaluated from these charts.

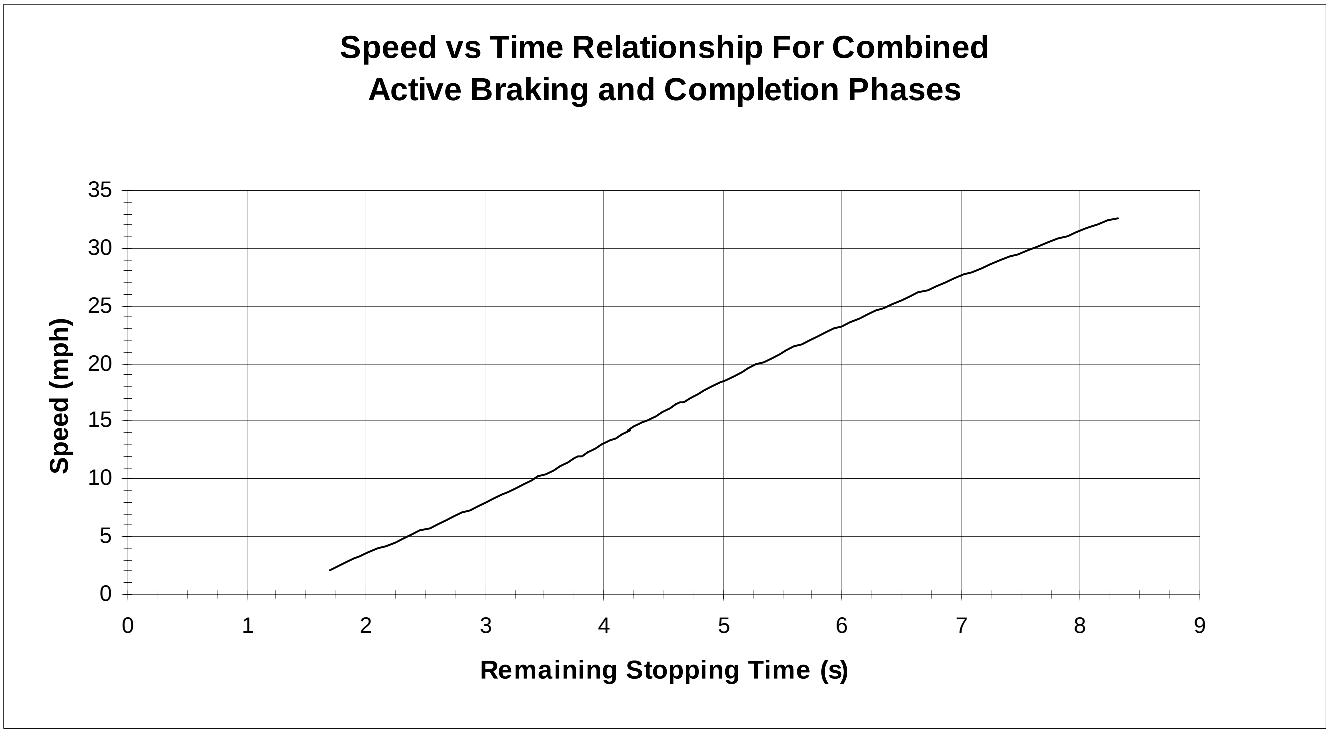

Figure B7. Speed/Time Relationship for Actively Braking Vehicles Decelerating to a Stop.

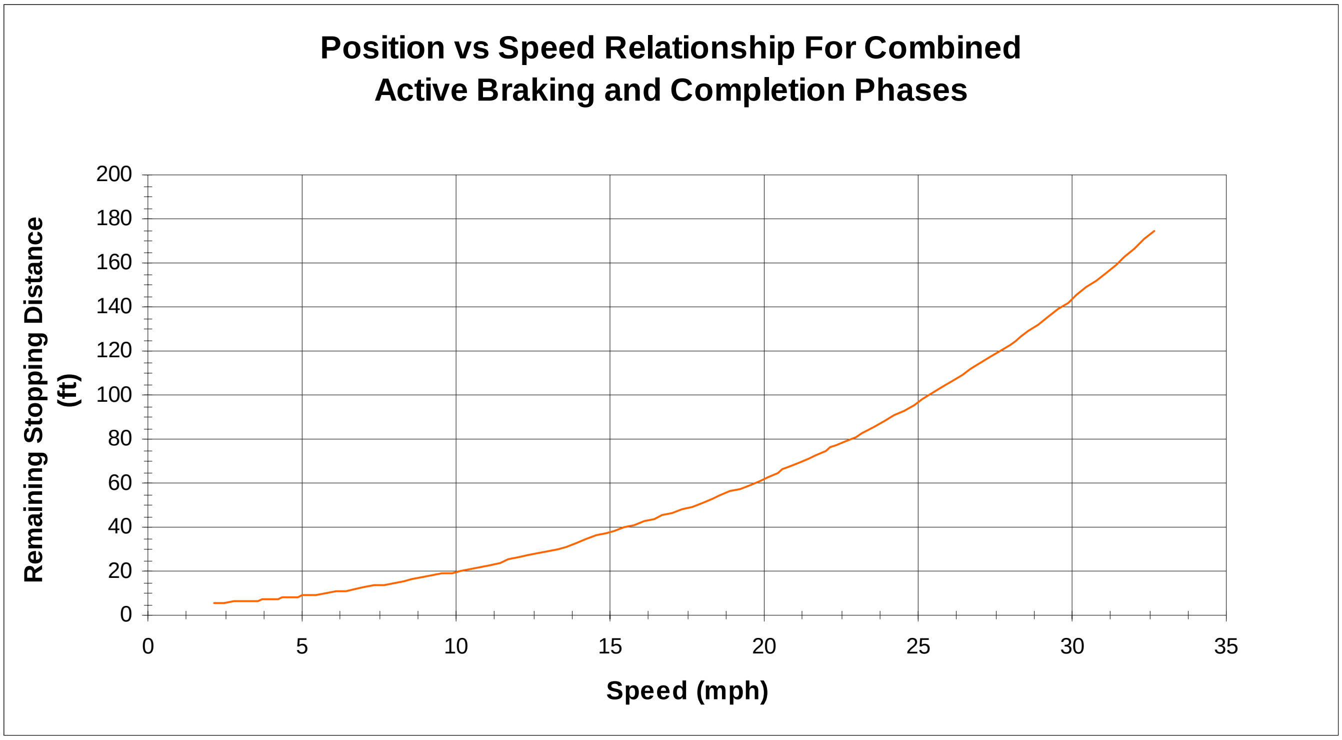

Figure B8. Position/Speed Relationship for Actively Braking Vehicles Decelerating to a Stop.

Calculation of a vehicle's pre-braking speed or the total distance and time required to stop a vehicle from a specific pre-braking speed necessitates consideration of all three phases. Table B4 presents bilinear model equations for the complete deceleration process. Figures B9 and B10 present these data in graphical form.

Table B4 — Complete Vehicle Stopping Process

	Initial Pre-Braking Speed	
	6.5 < V < 18.3 mph	18.3 < V < 37.2 mph
Total Stopping Distance d [m]	$d = \frac{V^2 + 9.40V - 5.75}{0.0624V + 3.51}$	$d = \frac{V^2 + 47.2V + 74.8}{14.1 - 0.124V}$
Total Stopping Distance t [s]	$t = \frac{1.6V - 10.4}{5.75 + 0.10V} + 4.8$	$t = \frac{1.6V - 29.5}{10.6 - 0.093V} + 7.2$
	Available Stopping Distance	
	24.6 < d < 108 ft.	108 < d< 364 ft.
Initial Pre-Braking Speed V [mph]	$V = 0.031d - 4.71 + \sqrt{0.00098d^2 + 3.24d + 38.01}$	$V = -(0.063d + 23.23) + \sqrt{0.0004d^2 + 17d + 485.3}$

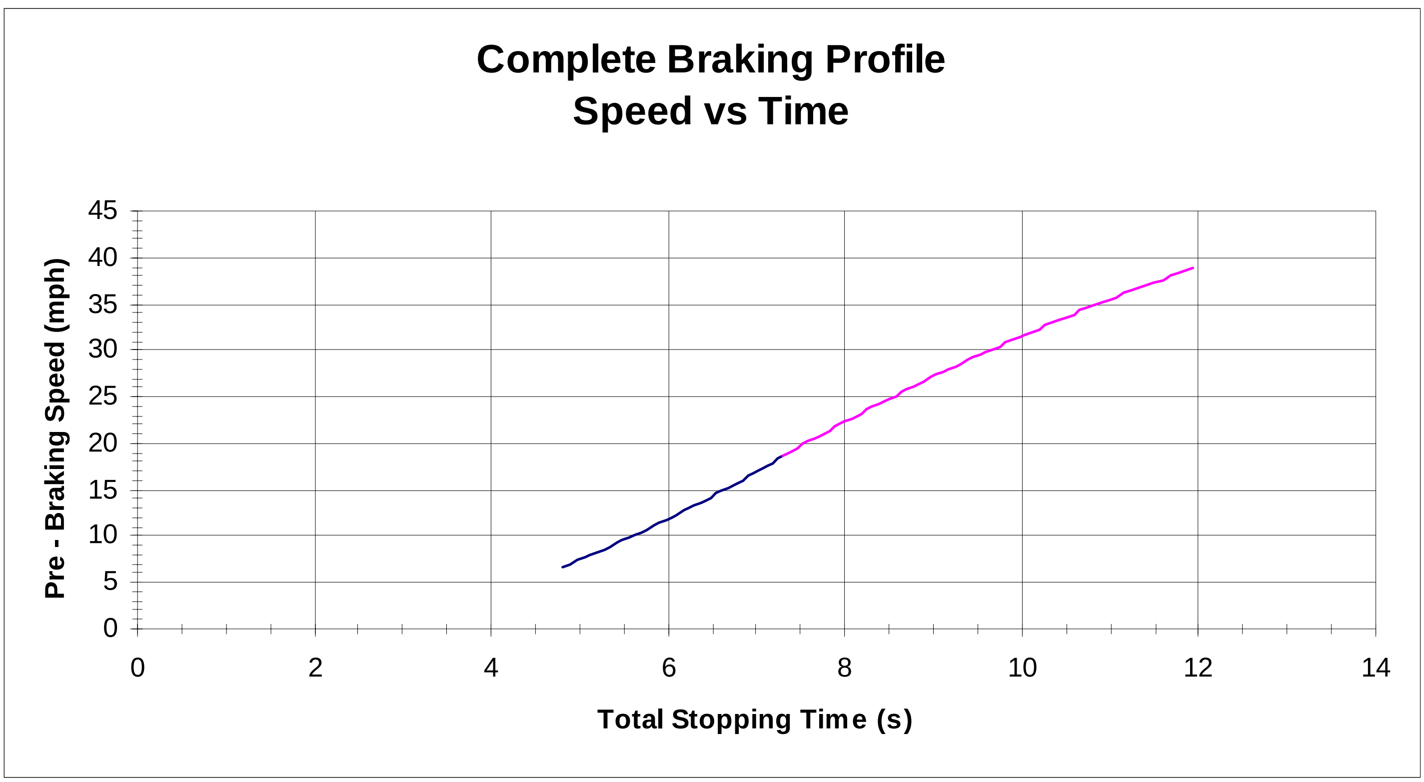

Figure B9. Speed/Time Relationship for the Complete Stopping Process.

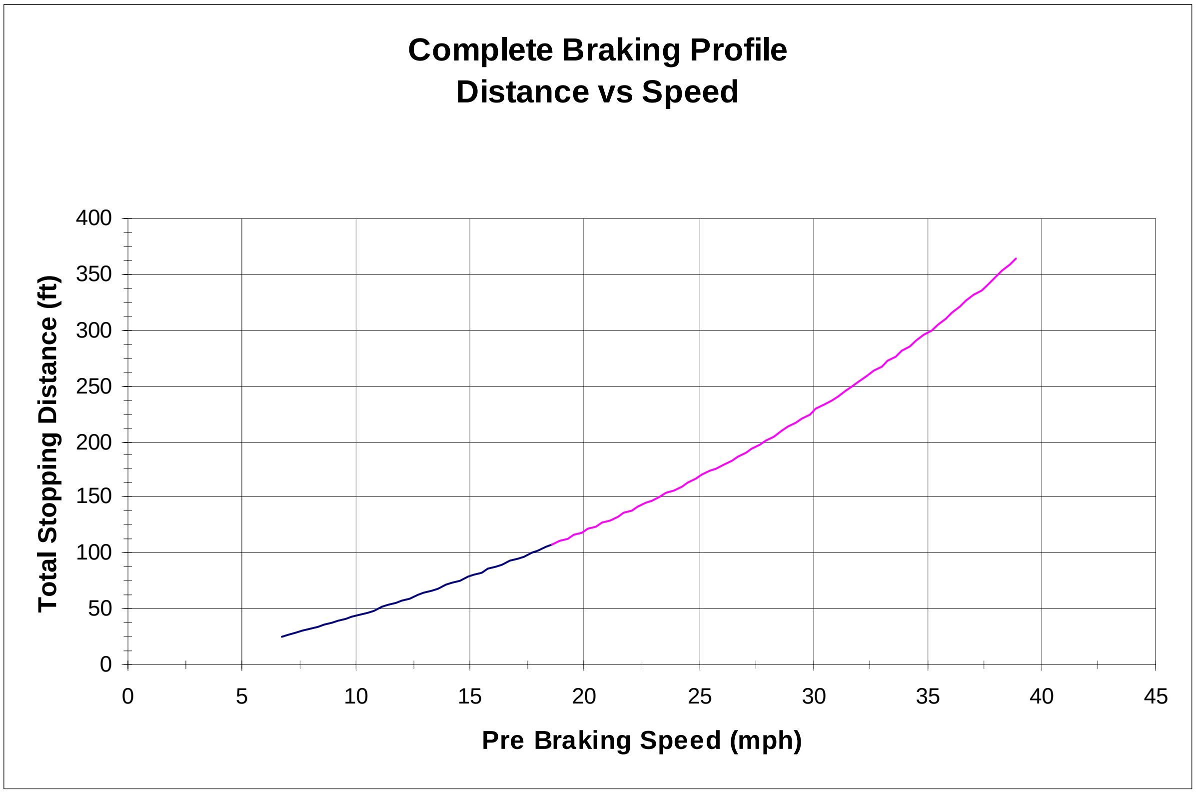

Figure B10. Position/Speed Relationship for the Complete Stopping Process.