

Acceleration Testing and Modeling of Vehicle Kinematics Under Idle Conditions

Bryan Randles, Daniel Voss, Isaac Ikram, Christopher Furbish,
Judson Welcher, and Thomas Szabo
Biomechanical Research & Testing

ABSTRACT

Determination of vehicle speed at the time of impact is frequently an important factor in accident reconstruction. In many cases some evidence may indicate that the brake pedal of a striking vehicle was disengaged, and the vehicle was permitted to idle forward prior to impacting the target vehicle. This study was undertaken to analyze the kinematic response of various vehicles equipped with automatic transmissions while idling, with the transmissions in drive and the brake pedals disengaged. An array of sedans, SUV's and pickup trucks were tested under 3 roadway conditions (flat, medium slope and high slope). The vehicle responses are reported and mathematical relationships were developed to model the idle velocity profiles for flat and sloped roadway surfaces.

CITATION: Randles, B., Voss, D., Ikram, I., Furbish, C. et al., "Acceleration Testing and Modeling of Vehicle Kinematics Under Idle Conditions," *SAE Int. J. Trans. Safety* 2(2):2014, doi:10.4271/2014-01-0484.

INTRODUCTION

Determining the speed of a vehicle at impact may be an important factor when determining the severity of a vehicle impact. Understanding how fast a vehicle will idle forward with the transmission engaged, foot off the brake and without application of the accelerator may be applicable to vehicle impacts commonly associated with heavy or stop-and-go traffic, right turn contacts with pedestrians, parking lot accidents, impaired or unconscious drivers or any other situation where a vehicle idles into an object.

Maximum accelerations for passenger vehicles are a frequently referenced vehicle performance parameter [1, 2, 3, 4, 5]. "Normal" or nominal accelerations from a stop have also been investigated [6, 7, 8]. However, very little published data is available regarding the speeds of passenger vehicles while idling forward with the automatic transmission engaged and no accelerator pedal application.

Some anecdotal references to vehicle idle speeds have been reported in event data recorder (EDR) related research. One such paper [9] included graphs showing a 2011 Toyota Camry, a 2010 Toyota 4Runner and a 2011 Toyota Prius had relatively constant "In 'Drive,' moving at idle speed" of approximately 8 to 9 km/hr (5.0 to 5.6 mph). The specific idle speed was not stated in the paper and is only displayed graphically in an [Appendix](#).

Idle testing by Rast, et al [10] utilized ten sedans, three sport utility vehicles and one minivan over level ground with the engines "warm." Peak and average acceleration were measured with a Valentine Research G-Analyst and maximum speed was measured with a Laser Technology LTI 20/20 laser speed gun. After the vehicle obtained maximum speed as measured by the LTI20/20, the vehicle was stopped. Across all vehicles, mean forward acceleration was 0.029 G's +/- 0.009 G's (mean +/- SD). Mean maximum forward speed was 3.5 mph. Peak and average acceleration correlated poorly with engine size and vehicle weight with correlation coefficients ranging from 0.15 to 0.42.

The most comprehensive compilation of vehicle idle speed tests were conducted and presented by Reust [11]. This study used 18 different vehicles, ranging from a 4-cylinder Toyota Prius to a Pumper type Detroit Diesel Fire Truck. Average level surface accelerations were found to be between 0.025 to 0.029 G's for the first 10 feet of motion. Level surface maximum speeds were 4.8 to 9.6 km/hr (3.0 to 6.0 mph) and were obtained after approximately 9.1 meters (30 feet) of travel. The author attempted to correct for uphill and downhill grades by several different methods including Grade Acceleration, Combined Acceleration, and Sum Acceleration and ultimately concluded that the "best method to determine speed is actual testing." [12]

TEST METHODOLOGY

The current study tested the idle speed of 23 passenger vehicles in three different roadway locations. Nine sedans, twelve SUVs and two pickup trucks were tested ([Table 1](#)). All vehicles were equipped with automatic transmissions.

Testing was conducted at three public roadway locations in the greater Long Beach, California area. The locations represented different roadway slope conditions: a nominally flat roadway surface [4], a medium sloped roadway surface, and a high sloped roadway surface. Each of the test locations were surveyed and the average slope over the total travel distance was utilized. All surfaces consisted of worn asphalt. [Table 2](#) contains a description of the roadways and the slopes and grades for each. The range of atmospheric conditions for the tests were 51.1 to 82° F, 29.83 to 30.27 in Hg (sea level pressure) and 34 to 73% humidity. All tests were conducted with the air conditioning in the off position.

Table 1. Test vehicles

Year	Make	Model	VIN
1999	Hyundai	Elantra	KMHJF35F6XUxxxxxx
2003	Saab	9-3	YS3FB49S531xxxxxx
2005	Chevrolet	Impala	2G1WF52E259xxxxxx
2006	Chevrolet	Malibu	1G1ZT51836Fxxxxxx
2006	Jaguar	S-Type	SAJWA01A06Fxxxxxx
2009	Toyota	Corolla	1NXBU40E19Zxxxxxx
2012	Subaru	Legacy	4S3BMB6C8C3xxxxxx
2013	Lexus	ES 350	JTHBK1GG3D2xxxxxx
2014	Volvo	S60	YV1612F57E2xxxxxx
1991	Ford	Explorer	1FMDU32XXMUxxxxxx
1996	Ford	Explorer (2)	1FMDU32P9TZxxxxxx
1999	Mercedes Benz	ML430	4JGAB72E3XAxxxxxx
1999	Toyota	RAV4	JT3GP10V9X7xxxxxx
2000	Ford	Expedition	1FMRU1563YLxxxxxx
2001	Nissan	Pathfinder	JN8DR09Y21Wxxxxxx
2003	GMC	Yukon	1GKEC16T43Jxxxxxx
2009	Subaru	Forester	JF2SH61619Hxxxxxx
2011	Acura	MDX	2HNYD2H56BHxxxxxx
2012	Volkswagen	Tiguan	WVGAV7AXXCWxxxxxx
2013	Jeep	Grand Cherokee	1C4RJFBG1DCxxxxxx
2013	Lexus	RX 450h	JTJZB1BA4D2xxxxxx
1992	Ford	F-150	1FTEF15H0NPxxxxxx
2001	Ford	F-150	1FTRW07L11Kxxxxxx

Table 2. Roadways and the average slope for total travel distance

Condition	Roadway	Avg. Slope (degrees)	Avg. Grade (%)	Travel Distance (feet)
Flat	Worn asphalt	0.13	0.22	514
Medium	Worn asphalt	1.19	2.09	258
High	Worn asphalt	2.75	4.80	209

Each vehicle was tested at least 4 times at each location, with at least 2 tests in the positive slope direction (uphill) and at least 2 tests in the negative slope direction (downhill), for a total of at least 12 tests on each vehicle. A start and end point for each location was predetermined. For each individual test the vehicle started in a stopped position with the brake engaged. Once data logging was initiated, the driver's foot disengaged the brake and did not depress the accelerator. The vehicle traveled the length of the roadway indicated in [Table 2](#) while the engine idled.

Vehicle displacement and speed were recorded using a Racelogic VBOX III. The VBOX III collects data at 100 Hz, with speed reported to be accurate to 0.1 km/h (0.06 mph) [13]. The approximate engine temperature and any special conditions were noted for each test. Engine idle speed (RPM) was not reported as many of the vehicles tested were not equipped with a tachometer. Additionally, absent an EDR download, engine RPM is not a parameter that is typically known in the context of accident reconstruction.

RESULTS

A total of 290 tests were performed. All data collected were filtered with a 6th order Butterworth filter with a 5 Hz cut-off in accordance with published GPS data filtering requirements [14]. The results of the tests were plotted and analyzed. With respect to the tests conducted on flat ground, no significant difference between the different directions of travel was found, and thus data were combined from both travel directions for the flat ground group.

Flat Ground Tests

[Figures 1](#) and [2](#) show the complete speed versus distance plots for the flat condition for sedans and SUVs/pickups, respectively. For most vehicles, steady-state velocities were reached after approximately 100 feet of travel on the flat condition. Using the average speed between 100 and 400 feet as steady-state, steady-state speed for sedans was 5.0 +/- 1.48 mph (mean +/- SD) and for SUVs/pickups was 4.71 +/- 0.75 mph.

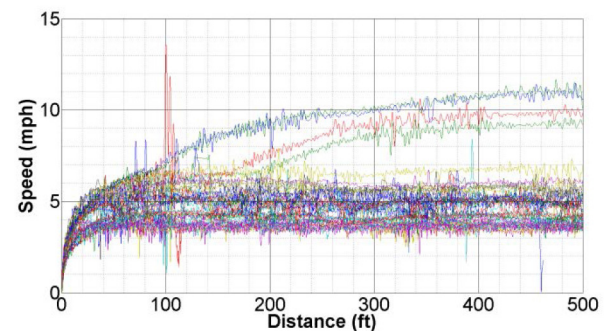


Figure 1. Sedan Speed v Distance for flat ground

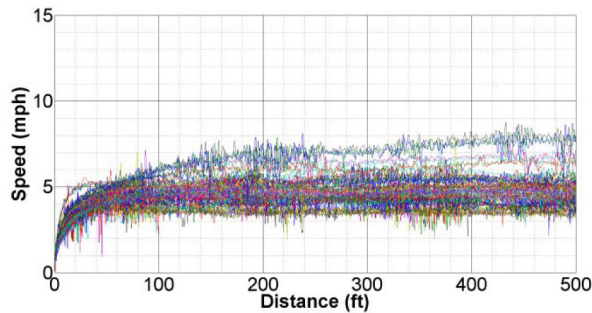


Figure 2. SUVs/Pickups Speed v Distance for flat ground

It can be seen in Figures 1 and 2 that some of the vehicles continued to accelerate and did not reach a steady-state travel speed in the 500 feet of travel. One of the sedans (Hyundai Elantra) that did not reach a steady-state speed actually shifted into second gear while traveling on the flat surface, as can be seen in the traces in Figure 1. However, for those vehicles not reaching a steady-state travel speed, statistical tests showed that these data were not considered outliers, and thus were included in the analysis.

Visual examination of the data collected on flat ground indicated an approximately bi-linear relationship between vehicle speed and distance traveled. The rate of speed increase was initially rapid and then became less as the vehicle approached an approximately steady-state speed. This type of relationship is similar to a first order step response. Accordingly, a first-order step response descriptive model was developed, taking the form of Equation 1:

$$v_v = A \left(1 - \frac{1}{e^{\frac{d}{D}}} \right) \quad (1)$$

Where:

v_v = velocity of the vehicle (mph)

d = vehicle distance traveled (feet)

A = constant (mph)

D = constant (feet)

From a theoretical standpoint the A value is the vehicle's steady-state speed, while the D value corresponds to the distance traveled prior to reaching steady-state speed. Increasing the value of D results in prolonging the distance required to reach steady state-speed.

The mean and upper and lower boundary of the 95th percent confidence interval (mean $\pm$ 2 SD) for speed was determined at 1 foot increments for all conditions, with test data from the same vehicles averaged for each condition prior to determining the statistical bounds.

In the accident reconstruction context, vehicle idling characteristics are typically of most interest over the initial 20 feet of distance traveled. Accordingly, the means and confidence intervals were modeled for the first 20 feet of travel. Modeling constants A and D in Equation 1 were iterated to maximize the R^2 value for the data set modeled. This resulted in an R^2 value of 0.94 or greater. The roadway slopes of the up and down slope conditions are reported in Table 3 for the first 20 feet of vehicle travel upon which the models were based.

Table 3. Equation 1 constants and R^2 for first 20 feet of travel on flat ground

Condition	Slope Direction	Slope (degrees)	Grade (%)
Flat	Down	-0.07	-0.12
	Up	0.20	0.35
Medium	Down	-0.92	-1.61
	Up	1.55	2.71
High	Down	-3.21	-5.61
	Up	2.41	4.21

Figures 3, 4, 5 contain the test data and model results for the first 20 feet for sedans, SUV/pickups, and then all vehicles combined, respectively. Table 4 contains the applicable A and D constants for these data.

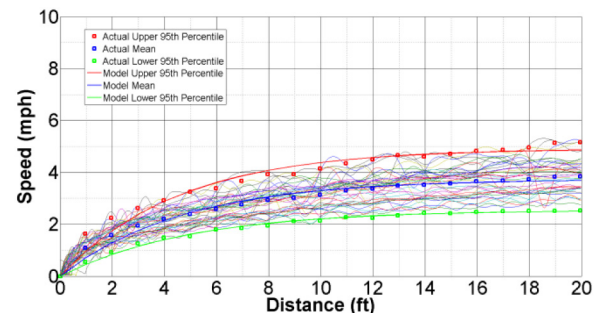


Figure 3. Sedan Speed v Distance for flat ground - model with upper and lower bounds

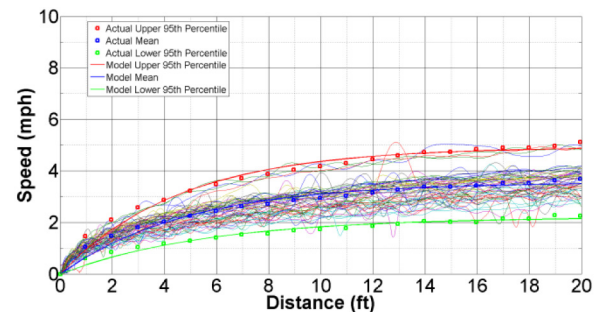


Figure 4. SUV/Pickup Speed v Distance for flat ground - model with upper and lower bounds

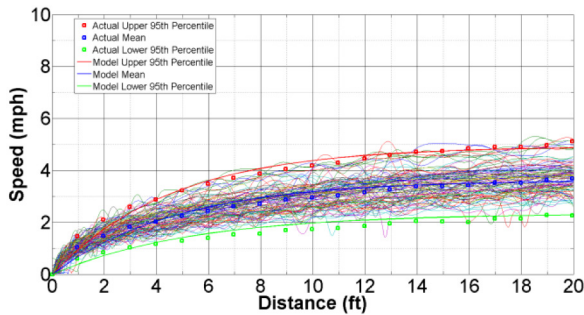


Figure 5. Combined Speed v Distance for flat ground - model with upper and lower bounds

Table 4. Equation 1 constants and R^2 for first 20 feet of travel on flat ground

Bound	Vehicle Class	A	D	R^2
Upper 95th	Sedan	4.92	4.53	0.96
Mean	Sedan	3.74	4.70	0.98
Lower 95th	Sedan	2.55	4.98	0.99
Upper 95th	SUV/pickup	4.93	4.60	0.98
Mean	SUV/pickup	3.56	4.88	0.98
Lower 95th	SUV/pickup	2.21	5.67	0.97
Upper 95th	Combined	4.93	4.56	0.97
Mean	Combined	3.63	4.80	0.98
Lower 95th	Combined	2.34	5.38	0.98

Figures 6 and 7 depict the modeled functions in the acceleration versus distance domain for the first 20 feet of travel. In order to convert the functions, Equation 2 was used and discrete average accelerations were determined over one foot segments. As shown in the figures, the acceleration initially rises very quickly before decreasing to near zero.

$$a_v = \frac{v_2^2 - v_1^2}{2 \times d_{step}} \quad (2)$$

Where:

$$a_v = \text{vehicle acceleration} \left(\frac{ft}{s^2} \right)$$

$$v_1 = \text{velocity at step1} \left(\frac{ft}{s} \right)$$

$$v_2 = \text{velocity at step2} \left(\frac{ft}{s} \right)$$

$$d_{step} = \text{length of step (feet)}$$

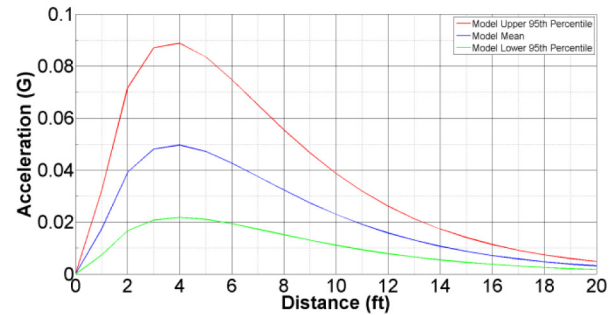


Figure 6. Sedan Acceleration v Distance for flat ground

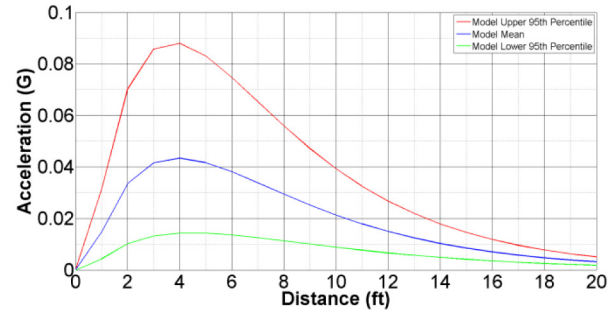


Figure 7. SUV/Pickup Acceleration v Distance for flat ground

Medium and High Slope Tests

The data for the medium and high slope test conditions were analyzed similarly to that for flat ground. Appendix A contains the data plots for the entire distance traveled for each condition. Appendix B contains the data with the confidence intervals and model results and Appendix C contains tables of the constants for the bounding equations of each sloped test condition.

DISCUSSION

The kinematic responses of various sedans, SUVs, and pickup trucks while idling from a stop were measured for 3 roadway conditions (flat, medium slope, and high slope). An analytical model was developed for the first 20 feet of travel, with data and mathematical relationships for sedans, SUV/pickups and all vehicles combined reported separately. The mathematical model quantified the idle velocity versus distance profiles for tested flat and sloped roadway surfaces.

There was no indication the distribution in the datasets was not normal. Although there was some difference between the data from the sedans and that from the SUVs/pickups, this difference was not found to be statistically significant. The range of average acceleration and velocity found in the current study were found to be similar to what has been previously reported [9, 10, 11].

An attempt was made to adjust the flat data equations for roadway slope and the adjusted model was compared to the results from the medium and high slope tests. The adjustment involved adding the proportion of gravitational acceleration, based on the slope of the roadway, to the flat ground

acceleration-distance relationship. The resulting velocity was then determined in a manner similar to numerical integration. This approach was determined to be unsuitable. The adjusted model tended to underestimate the measured speed while traveling upslope and overestimate the measured speed when traveling downslope. This is consistent with the findings of Reust [11], and indicates that parameters in addition to gravitational acceleration play a role in idle speed variation on sloped versus level surfaces.

CONCLUSIONS

- The first 20 feet of vehicle idle travel was adequately modeled as a first-order step response for flat and sloped roadway surfaces.
- The steady-state speed for sedans was 5.0 +/- 1.48 mph and for SUVs/pickups was 4.71 +/- 0.75 mph.
- Typically vehicles continued to accelerate beyond the first 20 feet of travel for the flat roadway slope condition.
- The flat roadway model could not be corrected for slope based on the gravitational contribution alone. This indicates that parameters in addition to gravitational acceleration play a role in idle speed variation on sloped versus level surfaces

REFERENCES

1. Webster, L.(Ed.), "Road & Track: Road-Tests," <http://www.roadandtrack.com/car-reviews/road-tests/>.
2. Loh, E. (Ed.). "MotorTrend: Road Tests" <http://www.motortrend.com/roadtests/>.
3. Fricke, L.B. "Traffic Accident Reconstruction Manual", Northwestern University, Evanston, IL, ISBN 978-0912642079, 1990.
4. SAE International Surface Vehicle Recommended Practice, "Vehicle Acceleration Measurement," SAE Standard J1491, Rev. July 2006.
5. Vomhoff, DW., Expert Autostats (V. 5.3.0), Computer software, La Mesa, CA. 2013.
6. Fugger, T., Wobrock, J., Randles, B., Stein, A. et al., "Driver Characteristics at Signal-Controlled Intersections," SAE Technical Paper 2001-01-0045, 2001, doi:10.4271/2001-01-0045.
7. Proctor, C., Grimes, W., Fournier, D., Rigol, J. et al., "Analysis of Acceleration in Passenger Cars and Heavy Trucks," SAE Technical Paper 950136, 1995, doi:10.4271/950136.
8. Kodsí, S. and Muttart, J., "Modeling Passenger Vehicle Acceleration Profiles from Naturalistic Observations and Driver Testing at Two-way-stop Controlled Intersections," SAE Int. J. Passeng. Cars - Mech. Syst. 3(1):45-56, 2010, doi:10.4271/2010-01-0062.
9. Brown, R., Lewis, L., Hare, B., Jakstis, M. et al., "Confirmation of Toyota EDR Pre-crash Data," SAE Technical Paper 2012-01-0998, 2012, doi:10.4271/2012-01-0998.
10. Rast P., Stearns, R., Allison, M., et al., "Acceleration Factors and Maximum Speeds Under Conditions of Idle Acceleration," Accident Investigation Quarterly, Summer 2000.
11. Reust, T.J., "Engine Idle Acceleration." Presentation at the ARC-CSI annual conference 2008.
12. Reust T.J., Personal communication and unpublished data, 2013.
13. Racelogic, "VBOX III 100Hz GPS Data Logger User Guide,"http://www.racelogic.co.uk/downloads/vbox/Manuals/Data_Loggers/RLVB3_Manual%20-%20English.pdf, 15/07/2011.
14. "Lane Departure Warning System Confirmation Test and Lane Keeping Support Performance Documentation," US Department of Transportation, National Highway Traffic Safety Administration, Office of Vehicle Safety, Office of Crash Avoidance Standards, February 2013.

CONTACT INFORMATION

Bryan Randles
Biomechanical Research and Testing, LLC
2201 N. Lakewood Boulevard, Suite 1865
Long Beach, CA 90815
brandles@brteng.com

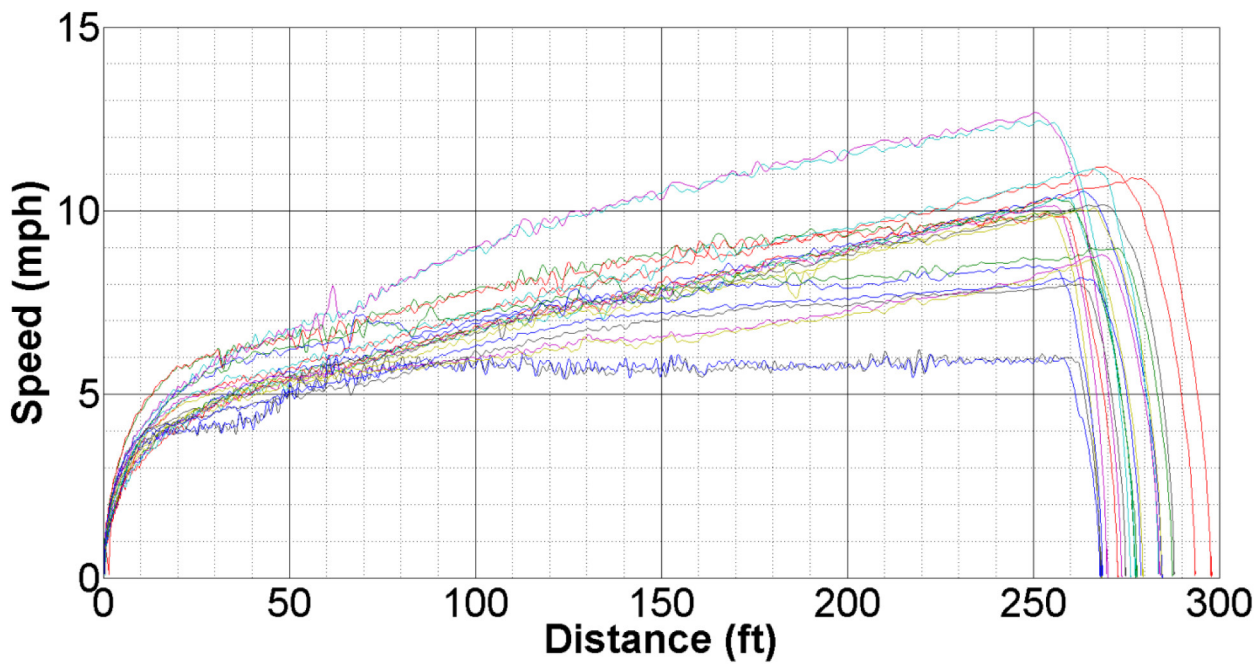
APPENDIX**APPENDIX A**

Figure A1. Sedan Speed v Distance for medium down slope - complete data set

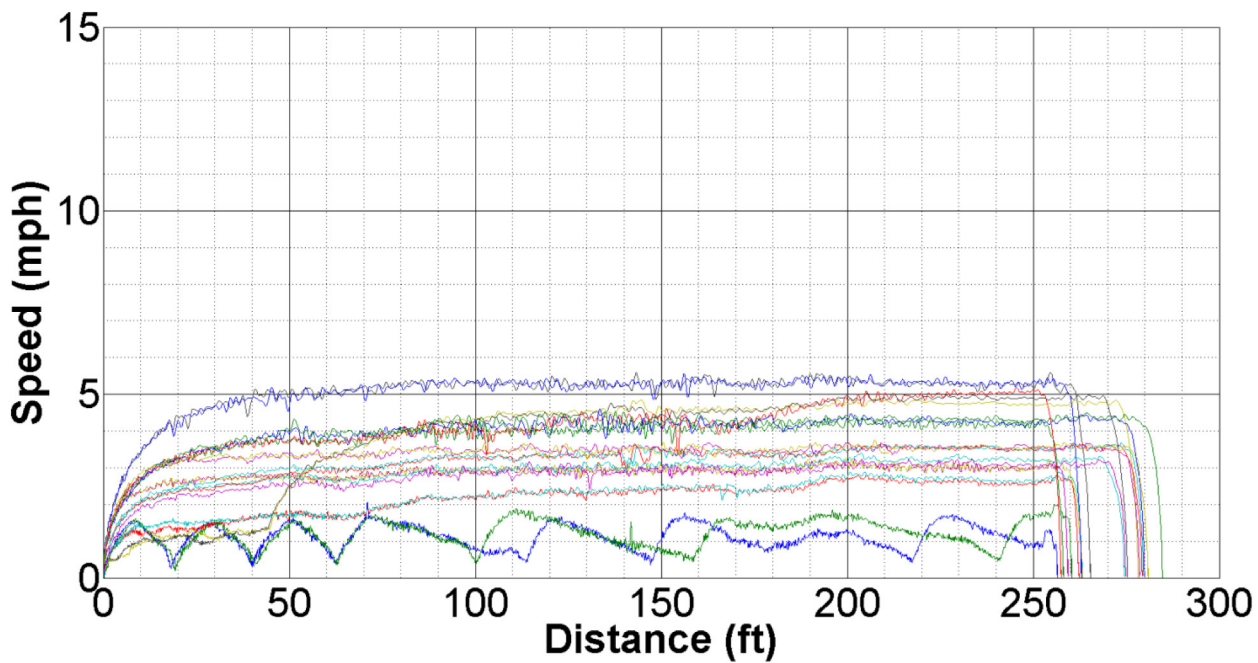


Figure A2. Sedan Speed v Distance for medium up slope - complete data set