

## CHAPTER 8. SYSTEM SIMULATION

### 8.1 Introduction

Simulation is a very powerful and widely used technique for analysis and study of complex systems. The systems which have numerous and stochastic parameters with complex relationships, it is very hard to come up with analytical models that would provide optimized solutions. Attempts to use analytical models for such systems usually require so many simplifications that the solutions are likely to be inferior or inadequate for implementation.

The level of complexity that surrounds the violation problem under study in terms of the numbers of factors and parameters that would shape the outcome of every violation, and the random nature of a lot of these parameters and their changing values over time necessitate the need to use simulation. The dominant reasons for use of simulation are:

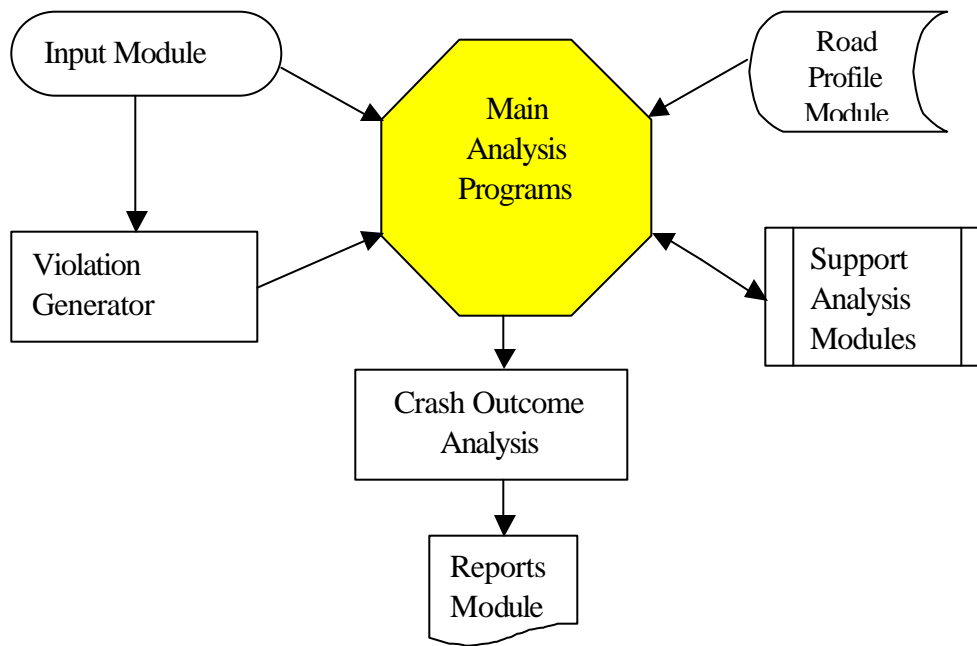
- 1- Understand better the violation problem and its happening, and what are the main factors affecting crash occurrences.
- 2- Get some estimation on how the system would perform under several scenario conditions, which could not be realized in the real world.
- 3- After validation, “what if “ tests could be used to assess the sensitivity of the outcome due to some limited modification of one or more parameter.

Actually, those three reasons combined would be very helpful in providing early answers about the system evaluation, which might instead require a prolonged period of field observation mainly because of the relatively low occurrences of the violations (less than 3 per day). However, that does not eliminate or diminish the necessity or importance of conducting such field surveillance, because it could verify the results of the simulation analysis and its conclusions, and on the other hand calibrate, modify and add some parameters in order to upgrade and reinforce the simulation model as a powerful tool in hand.

It is worth noting that no simulation packages in the current market have the capabilities to simulate centerline violations with limited passing sight distance on vertical curves. Therefore, a special code is written to perform such task through creating a microscopic, stochastic and period scanning simulation tool.

## 8.2 Code Structure

Simulation code was written in MATLAB of The MathWorks. MATLAB is a powerful modeling tool that integrates computation, graphics, and programming in a flexible open environment. The structure of the program is displayed in figure 8-1.



**Figure 8-1: Simulation Code Structure**

The simulation code consists of many program files that could be grouped into the following:

- 1- Input Module: it contains all input parameters that are going to be used by other program files either violations generation or in violation follow up subroutines or in the crash analysis.
- 2- Violation Generator: it generates randomly potential violations that would be picked up and initiated based on certain criteria or thresholds concerning relative speed difference and

- relative position between the violating vehicle (labeled A) and the vehicle being passed (labeled B), the absence of line of sight at  $t=0$  between violating vehicles A and the vehicle oncoming from the opposite direction (labeled C), the characteristics of the vehicles, vehicle A driver's conditions, etc.
- 3- Road Profile Module: consists mainly of roadway profile characteristics by direction put in look-up table format and expressed in terms of abscissa, elevation and grade for every 50-foot point along the roadway.
  - 4- Main Analysis programs: consist of the programs that simulate the violations generated, follow up the progression of takeover maneuvers and update data every 0.1-second step throughout the simulation period. These programs analyze all violations for "with" and "without" the system, and for different probable actions that the violator might take.
  - 5- Support Analysis Modules: are specific programs that tackle certain functions routinely required by the analysis such as updating the grade and altitude of vehicles A and C, determining eye elevations of drivers, identifying whether a line of sight is established between vehicles A and C, calculating time lags, etc.
  - 6- Crash Outcome analysis: consists of files that analyze the possible crashes observed when analyzing different cases in terms of number of occurrences, time of occurrences, crash speeds, etc.
  - 7- Report Module: are files generated as text files and summarize the crashes outcomes for every run. A run here could represent violations committed in one year (as in our case) or in any period of time. Violation progress could also be displayed graphically.

### **8.3 Defining the Input Parameters**

The simulation will allow the variation of many system parameters and study their impacts on the creation of accidents in a no-passing zone in a two-lane rural road. Actually, the system parameters may be classified into three groups, which are related to the three transportation system components:

- 1- Roadway-related parameters: horizontal layout, vertical profile, and lane configuration...

- 2- Vehicle-related parameters: location, speed, acceleration and deceleration, of the different vehicle classes involved in the incident.
- 3- Driver-related parameters: reflecting driver behavior and psychological conditions such as tendency to violate, perception time, reaction time and degree of being a risk-taker or risk averse.

Eventually, a large number of simulation runs could result from the combination of these above parameters. However, different scenarios based on certain assumptions are made in order to distinguish the impact of certain parameters on the system performance, and how that would consequently reduce the severity of the problem at hand.

### 8.3.1 Roadway Related Parameters

**Road profile:** As was described earlier, the road link under study includes a set of vertical curves with varying slope, except the 425-foot straight segment on the west side of the hill.

**Table 8-1: Road Profile and Grade by 50-Foot Step**

Curve coordinates		Grade	Curve coordinates		Grade	Curve coordinates		Grade
X	Z		X	Z		X	Z	
115.50	2019.00		123.00	2035.80	0.7			
116.00	2019.08	0.2	123.50	2035.98	0.4	130.50	2015.50	-4.2
116.50	2019.44	0.7	124.00	2035.80	-0.4	131.00	2013.40	-4.2
117.00	2020.12	1.4	124.50	2035.45	-0.7	131.50	2011.30	-4.2
117.50	2021.12	2.0	125.00	2034.85	-1.2	132.00	2009.20	-4.2
118.00	2022.43	2.6	125.50	2033.98	-1.7	132.50	2007.21	-4.0
118.50	2024.06	3.3	126.00	2032.88	-2.2	133.00	2005.43	-3.6
119.00	2026.00	3.9	126.50	2031.52	-2.7	133.50	2003.86	-3.1
119.25	2027.05	4.2	127.00	2029.92	-3.2	134.00	2002.50	-2.7
119.50	2028.07	4.1	127.50	2028.07	-3.7	134.50	2001.36	-2.3
120.00	2029.92	3.7	127.75	2027.05	-4.1	135.00	2000.32	-2.1
120.50	2031.52	3.2	128.00	2026.00	-4.2	135.50	1999.70	-1.2
121.00	2032.88	2.7	128.50	2023.90	-4.2	136.00	1999.20	-1.0
121.50	2033.98	2.2	129.00	2021.80	-4.2	136.50	1998.90	-0.6
122.00	2034.85	1.7	129.50	2019.70	-4.2	137.00	1998.72	-0.4
122.50	2035.45	1.2	130.00	2017.60	-4.2	137.50	1998.96	

The road profile is expressed as a series of 50-foot segments based on the coordinates and elevation readings of the road centerline as provided by VDOT plans. Table 8-1 exhibits the mile-

point of those readings ( $X$ ) and their respective elevations ( $Z$ ), from where we can calculate the average grade of those segments. The grades will be introduced in the kinematical analysis of the vehicle movement in the simulation as they affect in decreasing or increasing the speed of the vehicles.

Figure 8-2 depicts the  $X$  and  $Z$  readings, and a plan profile showing the 2-lane configuration of the road. The roadway profile in Figure 8-1 suggests that the actual distance “ $d$ ” is greater than 2100 feet, which is the horizontal projection, because of the grade and curvature of the road surface.

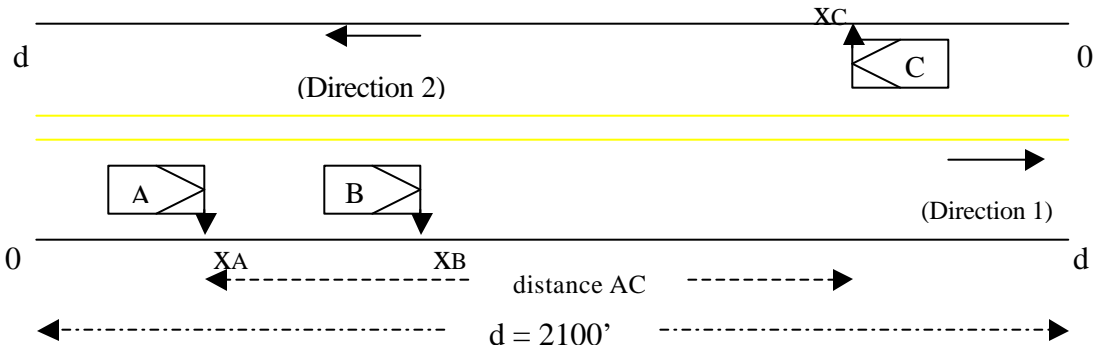
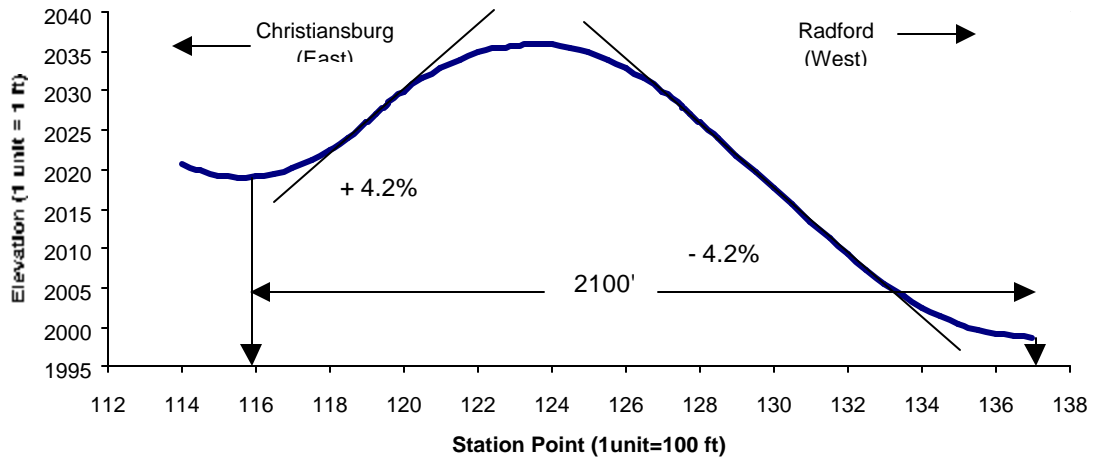
The exact calculation of the actual curve length would give about 2101 feet. So, we are going to ignore the additional 1-foot and consider it as a negligible error.

The two traffic directions will be separately treated in the kinematical analysis. Therefore, the exact location of every vehicle going eastbound or westbound at a certain moment of time “ $t$ ” will be referred to as the origin point of the vehicle direction (see Figure 8-1). For example:

$X_{vehA(t)}$  &  $vehA_{sp(t)}$  = Abscissa and velocity of vehicle A going **westbound** at time  $t$ .

$X_{vehB(t)}$  &  $vehB_{sp(t)}$  = Abscissa and velocity of vehicle B going **westbound** at time  $t$ .  $X_{vehC(t)}$

&  $vehC_{sp(t)}$  = Abscissa and velocity of vehicle C going **eastbound** at time  $t$ .



**Figure 8-2: Road Plan and Profile**

Based on the above, we may conclude that the abscissa values of the three vehicles will range from 0 to “d”. During the course of an illegal passing, a crash physically occurs when distance AC is zero, which could be expressed as follows:

$$\text{distance AC} = 0 \rightarrow d - (X_A + X_C) = 0 \rightarrow X_A + X_C = d .$$

The road profile and the location of vehicles play major roles in determining whether a line of vision could be established between vehicles A and C. Being able to see each other at a certain point of time, the process of next drivers’ action starts. This issue will be discussed in a coming section in further detail.

### **8.3.2 Vehicle-Related Parameters**

The figure above shows a sketch of the roadway geometry and the three vehicles contributing in the accident scenes. The vehicles are defined as follow:

- 1- A is the passing vehicle violator who tries to pass illegally vehicle B ahead,
- 2- B is the passed vehicle, and
- 3- C is the vehicle coming in the opposing direction

Violator vehicle A could belong either to light or to medium classes as we have seen in the violation survey, whereas B and C will belong to either category of the 3 vehicle classes. Such differentiation is established because each vehicle class has its own characteristics in terms of range of speed and acceleration capabilities. The vehicle classes' shares out of the total traffic mix, were determined based on a field traffic classification survey conducted during two representative weeks of September 2000. The vehicle classes and shares considered are:

- 1- Passenger cars (83%)
- 2- Medium vehicles (14%)
- 3- Heavy vehicles (3%)

A random uniform distribution will be used when assigning vehicles in violation simulations.

#### **8.3.2.1 Vehicle length**

The standard length for passenger car =19 feet and 30 feet for SU (AASHTO). Medium vehicles length will be 24 feet. This parameter should is important in order to determine the minimum distance between A and B to start a passing maneuver.

#### **8.3.2.2 Vehicle height**

A recent study was conducted by Fitzpatrick et al. (1998) reviewed the driver eye and vehicle heights for use in geometric design. The research was based on a field study of 875 passenger cars, 629 multipurpose vehicles (light truck and SUV) and 163 heavy vehicles. Table 8-2 depicts the recommended values, which present the 10<sup>th</sup> percentiles or 90% of the drivers' eye and vehicles height distribution. These values are adopted in the simulation that is presented in this chapter for determining the visibility and blind spots for the vehicles A and C approaching one another.

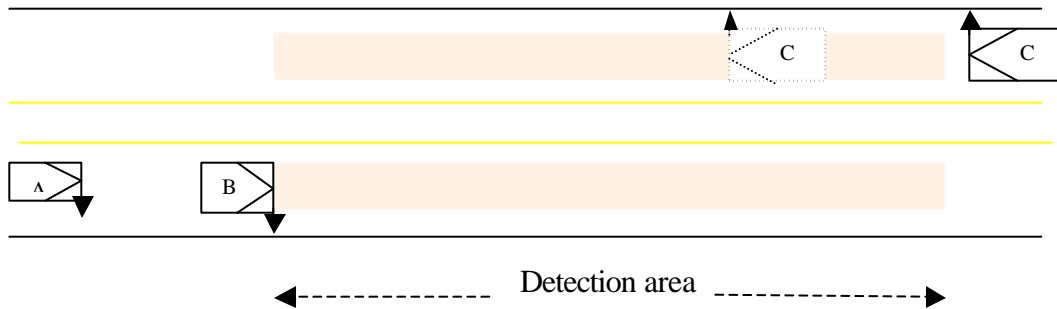
**Table 8-2: Driver’s Eye and Vehicle Heights**

	EYE HEIGHT		VEHICLE HEIGHT	
	Millimeters	Feet	Millimeters	Feet
AASHTO Passenger car	1070	3.5	1295	4.25
Passenger Car (LV)	1082	3.6	1315	4.3
Multipurpose Vehicles (MV)	1306	4.3	1564	5.1
Heavy Vehicles (HV)	2329	7.6	2719	8.9

**8.3.2.3 Vehicle Location**

Each of the three vehicles involved need to be located initially as simulation starts at time = 0. After that, kinematic laws and vehicles parameters (acceleration, deceleration and speed) drive the determination of vehicle locations.

The initial time (time=0) will be considered as the moment when vehicle B enters the detection area followed by vehicle A. vehicle C coming in the opposite direction could be inside or outside the detection area, as shown in Figure 8-3.



**Figure 8-3: Initial locations of vehicles**

Location of vehicle A: Referring to the field surveys conducted, violations were associated with a range of flow and speed distributions in both directions. It was found that violations were taking place during low traffic flow (mostly at level of service C or better). At time = 0 the volume and speeds are selected randomly from their distributions. Therefore, we can determine the mean of desired spacing between vehicles A and B using the basic traffic flow model:



$$q = ku_B \rightarrow d_d = \frac{1}{k} = \frac{u_B}{q} = \text{Mean desired spacing}$$

Where:  $q$  = traffic volume per unit time

$u_B$  = The vehicle speed

$k$  = traffic density ( inverse of spacing)

However, vehicle A driver, as a potential violator, seeks to narrow the distance with vehicle B before he/she starts their passing maneuver. This distance between the two vehicles should be greater than or equal to the minimum spacing determined by the Pitts car-following model (Halati 1996):

$$d_{AB} = L + 10 + ku_A + bk(u_B - u_A)^2 \quad (\text{In feet})$$

Where:

$d_{AB}$  = space headway between the lead vehicle B and the follower A.(from front bumper to front bumper)

$L$  = lead vehicle (B) length.

$u_A$  &  $u_B$  = speed of vehicles A and B.

$b$  = calibration constant defined as 0.1 (when  $u_A > u_B$ ) or 0 otherwise.

$k$  = driver sensitivity factor for the follower vehicle A that can range from 1.6 for timid driver to 0.3 for aggressive drivers.

Having all parameters at time = 0, a minimum distance  $d_{ABmin}$  could be then calculated for the aggressive violator:

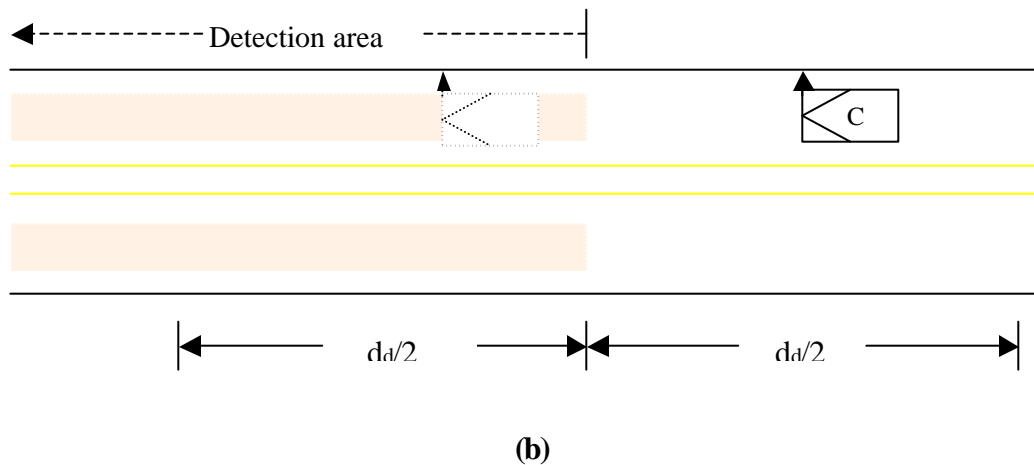
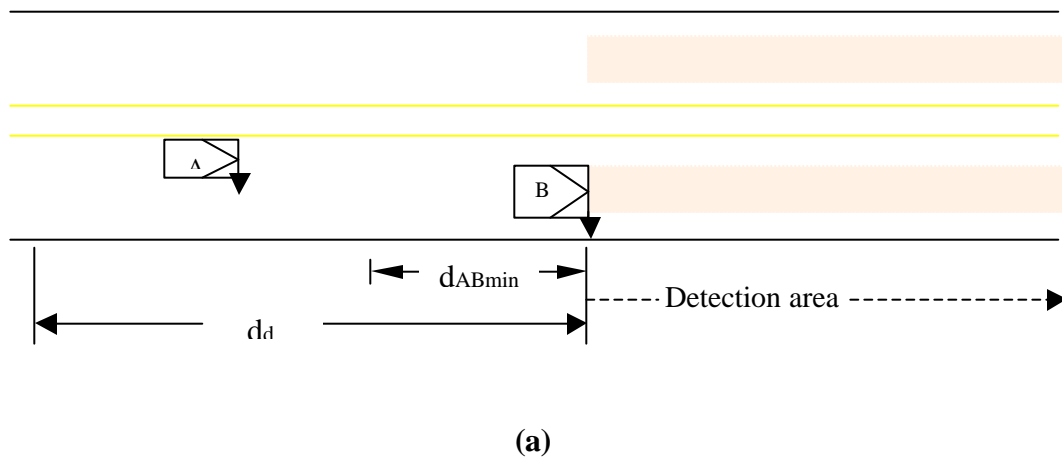
$$d_{ABmin} = L + 10 + 0.3u_A + 0.03(u_B - u_A)^2$$

As a conclusion, the violating vehicle A location at time = 0 is randomly selected between the mean desired spacing  $d_d$  and the minimum headway  $d_{ABmin}$ .

Location of vehicle C: Similarly for vehicle C, a mean desired spacing was calculated based on random headway based on the density-flow relationship for the traffic flow in the opposite direction. Since vehicle C could be located either inside or outside the detection area, the spacing segment was equally extended between inside and outside the detection area. The location of vehicle C was randomly selected along that segment.

Based on above, the assumptions result in the following chain of implications:

- 1- At time = 0, vehicles A and C drivers cannot see each other. If not, vehicle A driver, the potential violator, would see vehicle C coming from the other direction, hence, he/she would not start his/her illegal maneuver.
  - 2- Consequently, the two vehicles A and C would be initially located on the two sides of the vertical curve.
  - 3- Violations simulated are for those taking place in the upgrade side of the detection area.
- The system has no impact on the passing maneuvers taking place before vehicle B reaches the detection area where A in that case has enough sight distance to decide whether or not pass vehicle B.



**Figure 8-4: Initial Locations Determination of Vehicles A & C**

Figure 8-4, a and b illustrate the range of locations for vehicle A and C at time zero.

### 8.3.2.4 Vehicle speed

The vehicle initial speed was computed based on the observed speed distribution for every vehicle class. However, we may visualize the development of speed of the three vehicles while simulating the passing maneuver as follow:

- Vehicle B speed remains constant throughout the entire.
- Vehicle C speed remains constant with one exception that when vehicles C and A are revealed to each other, it is assumed in this case that the driver of vehicle C would intuitively try to reduce his/her speed to avoid a probable collision with A.
- Vehicle A speed varies depending on the acceleration or deceleration rates introduced during the passing course.

Initial speed (at  $t = 0$ ,  $x = 0$ ) for each vehicle is randomly distributed following the normal probability density function as presented in table 8-3. Initial speed distribution depends on the vehicle class and direction as well, simulating what have been observed during field surveys.

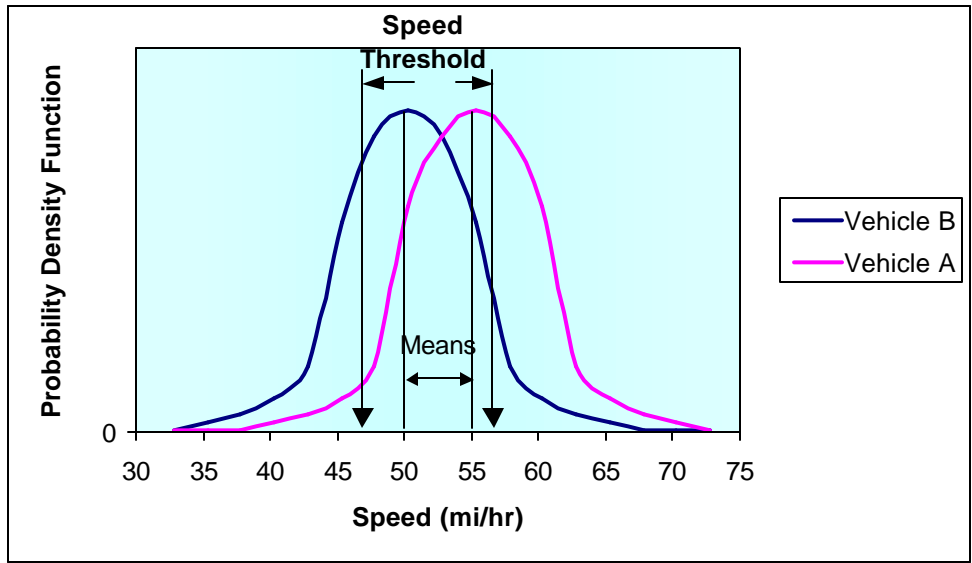
**Table 8-3: Normal PDF of Initial Speeds**

Vehicle Class	Light Vehicles		Medium Vehicles		Heavy Vehicles	
	East	West	East	West	East	West
Mean - $\mu$	54	52	54	51	53	50
St. Dev.-s	5	5	5	5	5	5

However, as vehicles A and B are running in the same directions with the assumption that B has lower speed than the potential violator A, two arrangements have been made:

- 1- The mean of the speed distribution of vehicle B was assumed 5 mi/h less than the mean of vehicle A for the same vehicle type, and
- 2- A speed variance threshold between vehicles A and B was set for taking over to start. This threshold is assumed randomly distributed from 5 to 10 miles per hour.

Figure 8-5 illustrates the concept of the assumed speed distributions and the speed variance threshold of vehicles A and B.



**Figure 8-5: Speed Distribution and Threshold of Vehicles A & B**

**8.3.2.5 Acceleration rate**

Acceleration is considered for the violating vehicle A only. This variable depends on three parameters:

- 1- The vehicle class (light vehicle or medium vehicle only),
- 2- The vehicle dynamics, and
- 3- The road grade.

**Overtaking and Passing (Acceleration) Performance**

Drivers overtake and pass at accelerations in the sub-maximal range in most situations. The maximum acceleration capabilities of passenger vehicles typically range from almost 3 m/sec<sup>2</sup> to less than 2 m/ sec<sup>2</sup> from 0 to highway speed.

Research has demonstrated that overtaking acceleration is typically 65 percent of the maximum acceleration for a vehicle under “unhurried” circumstances (ITE 1992). However, because of the illegal nature of the maneuver that is being considered, it is assumed that the driver of vehicle A is “hurried” and thus accelerates at the maximum acceleration rate while overtaking vehicle B.

The same source above provides an approximate equation for acceleration on a grade:

$$a_{GV} = a_{LV} - \frac{GxG_g}{100}$$

Where,

$a_{GV}$  = Max acceleration rate on grade

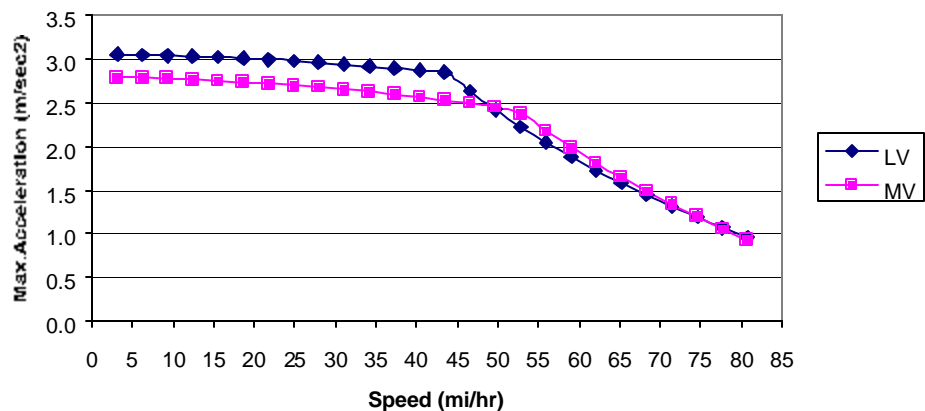
$a_{LV}$  = Max acceleration rate on level

G = gradient

Gg = acceleration of gravity ( $9.8\text{m/sec}^2=32.2\text{ ft/ sec}^2$ )

To establish models for the relationship between the maximum acceleration at level grade and speed for light and medium vehicles, we have applied the proposed model validated through a paper issued by (Rakha et al., 2001) which presents a simple vehicle dynamics model for estimating maximum vehicle acceleration levels based on a vehicle's tractive effort and aerodynamic, rolling, and grade resistance forces.

In addition, typical model input parameters for light and medium vehicles such as engine power, vehicle mass, vehicle altitude and frontal area, have been introduced and typical maximum acceleration –speed relationship were established and depicted in figure 8-6 for both vehicle types.



**Figure 8-6: Maximum Acceleration-Speed Relation At Level Grade**

The curves obtained show that maximum acceleration at rest is slightly greater than  $3\text{m/ sec}^2$  for light vehicles and around  $2.8\text{m/ sec}^2$  for medium vehicles, and decreases slightly till a certain point of speed after which the rate decreases at a higher rate to become less than  $1\text{m/ sec}^2$  for speeds above 80 mph. Based on above, we may approximate the curves shown in Figure 8-6 that relate maximum acceleration to speed at level grade into broken linear curves expressed by the following linear models:

For light vehicles:  $a_A = 3.281(3.1 - 0.0069u_A) \dots \text{when} : u_A \leq 43.5\text{mph}$   
 $a_A = 3.281(4.9 - 0.0483u_A) \dots \text{when} : u_A > 43.5\text{mph}$

For medium vehicles:  $a_A = 3.281(2.8 - 0.0076u_A) \dots \text{when} : u_A \leq 52.8\text{mph}$   
 $a_A = 3.281(5.23 - 0.0536u_A) \dots \text{when} : u_A > 52.8\text{ph}$

Where:

$a_A$  = Maximum acceleration for vehicle A (in ft/ sec<sup>2</sup>)

$u_A$  = Vehicle A speed (mph)

### 8.3.2.6 Deceleration

Deceleration is constant. It consists also of two factors:

- 1- The braking friction forces.
- 2- The gravity component parallel to the road due to road grade.

### Braking (Deceleration) Performance

A research conducted by Fambro et al.(1994) provides some controlled braking performance data of direct application to performance modeling. "Steady state" approximations or fits to these data show wide variations among drivers, ranging from **-0.46 g** to **-0.70 g**. Table 8-4 provides some steady-state derivations from empirical data collected by Fambro et al. These were all responses to an unexpected obstacle or object encountered on a closed course, in the driver's own (but instrumented) car. Table 8-4 provides also the same derivations from data collected on drivers in their own vehicle in which the braking maneuver was anticipated.

**Table 8-4: Percentile Estimates of Steady-State Deceleration**

	<b>Unexpected</b>	<b>Expected</b>
Mean	-0.55	-0.45
Standard Deviation	0.07	0.09
75 <sup>th</sup> percentile	-0.43	-0.36
90 <sup>th</sup> percentile	-0.37	-0.31
95 <sup>th</sup> percentile	-0.32	-0.27
99 <sup>th</sup> percentile	-0.24	-0.21

The driver knows that he or she would be braking, but during the run were unsure when the signal (e.g. a red light inside the car) would come. The ratio of unexpected to expected closed-loop

braking effort was estimated by Fambro et al. to be about 1.22 under the same pavement conditions.

The means and standard deviations shown above were adopted to simulate the braking deceleration for vehicle A (i.e. expected deceleration) and C (i.e. unexpected deceleration) regardless of the vehicle class.

### **8.3.3 Driver-Related Parameters**

#### **8.3.3.1 Violating passing rate**

Violating passing rates depends on three major conditions:

**A-** The objective situation factors, which may altogether, create the incentive to make a pass when it is legally permitted. These factors are those traditionally considered in passing rates estimation models such as:

- 1- Differential speed between vehicles A & B
- 2- Traffic volume
- 3- Relative positions of A and B on the road

**B-** The driver tendency (or willingness) to commit an illegal action that is violating the “No Passing” regulation.

**C-** Where the driver’s position is as a risk-taker when deciding to make a passing maneuver.

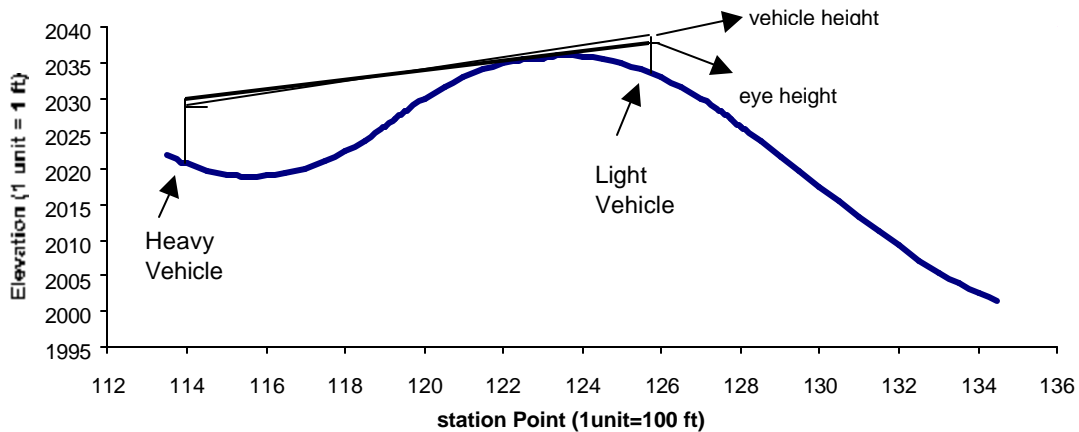
The last two conditions are purely human factors that require special study that is beyond the scope of this research.

Anyway, violating takeovers in this study is based on field observations in which illegal takeovers were committed with short passing sight distance in both directions. The field observation resulted in 3.4 violations per 10,000 vehicles in the eastbound direction and 0.8 violations per 10,000 vehicles in the westbound direction. These violation rates correspond approximately about 720 and 170 violations committed with no enough passing sight distance per year in the eastbound and westbound directions, respectively.

### 8.3.3.2 Visibility between vehicles A and C

Due to the road profile, visibility between the two vehicles A and C cannot take place unless the two vehicles are positioned at appropriate points of location that allow a line of sight to be established between the eye of the driver of one vehicle and the top of the second vehicle coming in the opposite direction.

Here a question could be posed about which vehicle driver might see the other first: vehicle A or C?



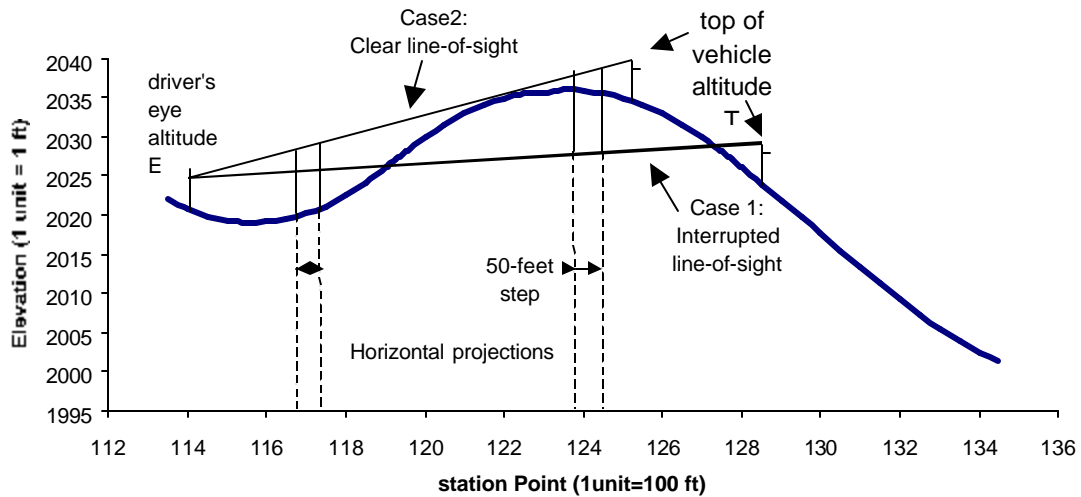
**Figure 8-7: Lines-of-Sight Between Typical Heavy And Light Vehicles**

Actually as figure 8-7 shows, there are small differences between the distances between the driver's eye and the top of the vehicle for the different types of vehicles (ranges from 0.7 to 1.3 feet). These distances in turn are very small when compared to the distance separating A and C (the vertical scale is magnified 100 times the horizontal scale). Hence, the time difference between the events of seeing each other is a small fraction of a second. Therefore, it is assumed that vehicles establish visual contact at the same instant of time.

Now the process which determines whether a clear line-of-vision is established between the two cars, is based on the fact that, no physical obstacle should interrupt the line of sight between the eye of one vehicle driver and the top of the other vehicle.



The process adopted to establish whether vehicles can observe one another consists of the following steps (see Figure 8-8):



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Figure 8-8: Line-Of-Sight Verification

- 1- Assess the horizontal location of vehicle A and C at time  $t$
- 2- Using the road vertical profile data, estimate the elevation of vehicles A and C using interpolation.
- 3- Knowing the type of both vehicles, determine the altitude of the eye of vehicle A driver ( $E_t$ ), and the top of vehicle C ( $T_t$ ).
- 4- Establish the line-of-sight between E and T.
- 5- Along the line ET, locate a series of points at 50-foot increment starting from E towards T.
- 6- Determine the elevations of the series of points identified in step 5, (dotted lines in the figure) along the line of sight between points  $E_t$  and  $T_t$ .
- 7- Referring to the road profile, compute the roadway elevations along the series of points identified in step 5.
- 8- Compare the altitude of the points along the line-of-sight, and the altitude of the road having same vertical projection.
- 9- A clear line-of-sight will be established at time instant  $t$ , if the altitudes of **all the points**, along the line of sight ET, are higher than those of the road profile, which have the same vertical projection.

10- In the case that the condition of step 9 is not satisfied by at least in one point, it is assumed that vehicles A and C cannot establish a visual contact at time instant  $t$ .

11- Repeat the entire process in the subsequent time step  $t + 1$  (next deci-second).

Figure 8-7 represents two cases of line -of- sight: Interrupted in case 1 and clear in case 2.

### **8.3.3.3 The human factor parameters assessments**

In microscopic simulation, the driver of the vehicle is governed by a complex environment created by the numerous analytical factors intervening in shaping the overall performance of the road-driver-vehicle system.

In this section we are going to focus on the human behavior when performing the driving task and we will try to determine some human factors that would pertain our problem especially the perception-reaction time, control movement time, (steering, braking and speed control), and responses to the presentation of traffic control devices.

The examination of such human performance requires - like any other human behavior – consideration of individual differences i.e. inter- and intra- driver variability. For instance, when measuring braking response, two drivers could react differently under identical environmental conditions, and the same driver could act differently under different environmental conditions as well (normal driving versus intoxicated driving conditions).

The following description of this section is based on the revised version of “Traffic Flow Theory“(1996), namely the “Human Factors” chapter written by Rodger J. Koppa.

### **8.3.3.4 The Driving Task**

Lunenfeld and Alexander (1990) consider the driving task to be a hierarchical process, with three levels: (1) Control, (2) Guidance, and (3) Navigation. The **control** level of performance comprises all those activities that involve second-by-second exchange of information and control inputs between the driver and the vehicle. Most control activities, as pointed out, are performed "automatically" with little conscious effort. In short, the control level of performance is *skill based*. The next level of human performance is the *rules-based guidance* level. The driver's main activities "involve the maintenance of a safe speed and proper path relative to roadway and traffic elements. Guidance level inputs to the system are dynamic speed and path responses to roadway

geometrics, hazards, traffic, and the physical environment. Information presented to the driver-vehicle system from traffic control devices, delineation, traffic and other features of the environment, is continually changing as the vehicle moves along the highway.

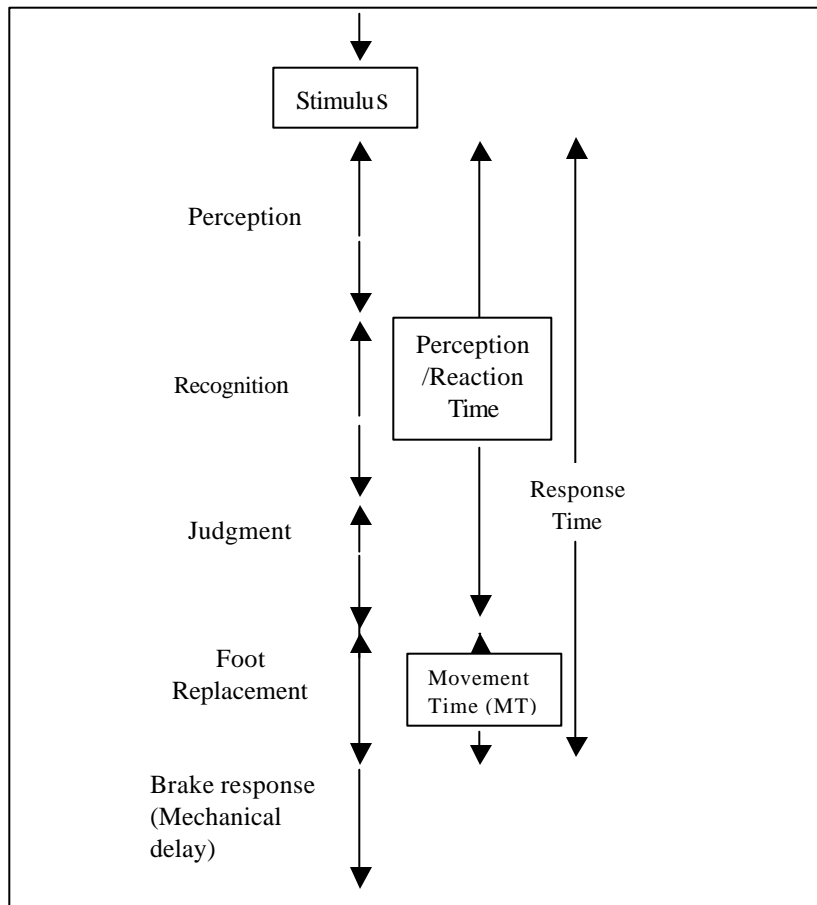
The third (and highest) level in which the driver acts as a supervisor is *navigation*. Route planning and guidance while en-route, for example, correlating directions from a map with guide signage in a corridor, characterize the navigation level of driver performance.

Some would call this level *knowledge-based behavior*.

The first two levels of driving tasks- control and guidance- are of paramount concern to modeling a potential accident on a highway facility.

### 8.3.3.5 Perception-Reaction Time (PRT)

Perception-reaction time is the lag in time between detection of an input (stimulus) and the start of initiation of a control or other response.



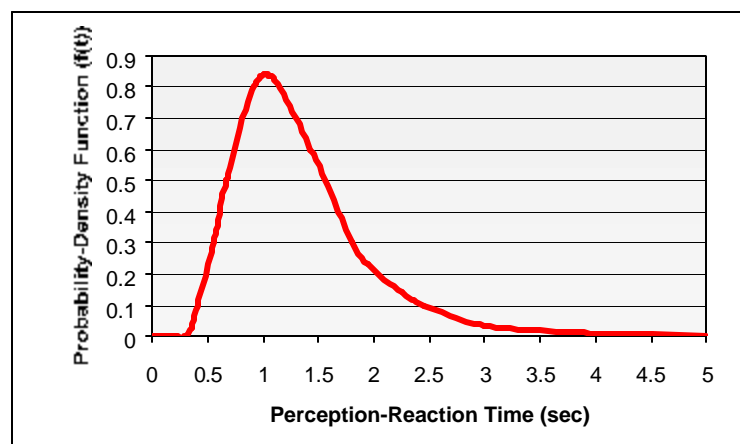
**Figure 8-9: Reaction/Response Time**

If the time for the response itself is also included, then the total lag time is termed the "response time." Often, the terms "reaction time" and "response time" are used interchangeably, but one the reaction time is always a part of the other response time as illustrated in Figure 8-9. Therefore, a driver's braking response could be viewed as composed of two parts, prior to the actual braking of the vehicle: the perception-reaction time (PRT) and immediately following, movement time (MT). Several PRT models have been *chaining* individual components of the time lag that are presumably orthogonal or uncorrelated with one another. Hooper and McGee (1983) postulated a very typical and plausible model with such components for braking response time (including movement time MT), illustrated in Table 8-5.

Figure 8-10 depicts the actual shape of probability distribution of the PRT.

**Table 8-5: Breakdown of PRT (85<sup>th</sup> Percentiles)**

Component	Time (sec)	Cumulative Time (sec)
<b>1) Perception</b>		
Latency	0.31	0.31
Eye Movement	0.09	0.4
Fixation	0.2	1
Recognition	0.5	1.5
<b>2) Initiating Brake Application</b>	1.24	2.74



**Figure 8-10: Probability Distribution Function of PRT**

Each component of the PRT elements is derived from empirical data, and the data shows the 85th percentile estimate for that aspect of time lag. Because it is doubtful that any driver would produce 85th percentile values for each of the individual elements, 1.5 seconds probably represents an extreme upper limit for a driver's perception-reaction time. This is an estimate for the simplest kind of reaction time, with little or no decision-making. The driver reacts to the input by lifting his or her foot from the accelerator and placing it on the brake pedal. But a number of authors, for example Neuman (1989), have proposed perception-reaction times (PRT) for different types of roadways, ranging from 1.5 seconds for low-volume roadways to 3.0 seconds for urban freeways. There are more things happening, and more decisions to be made per unit block of time on a busy urban facility than on a rural county road. Each of these added factors increases the PRT.

#### ***8.3.3.6 Surprised vs. expected PRT***

A literature review by Lerner et al. (1995) includes a summary of brake PRT (including brake onset) from a wide variety of studies. Two types of response situations were summarized:

- 1- The driver does not know when or even if the stimulus for braking will occur, i.e., he or she is surprised, which represents a real-world occurrence on a roadway; and
- 2- The driver is aware that the signal to brake will occur, and the only question is when.

The composite data of sixteen studies of braking PRT were converted to a log-normal transformation to produce the accompanying Table 8-6. Note that the 95th percentile value for a "surprise" PRT (2.45 seconds) is very close to the AASHTO estimate of 2.5 seconds which is used for all highway situations in estimating both stopping sight distance and other kinds of sight distance (Lerner et al. 1995).

Based on the above, this research adopts the perception/reaction times that are summarized in the Lerner review. Furthermore, the reaction/response time in the simulation is considered as a random normally distributed parameter with mean and standard deviation as summarized in Table 8-6.

**Table 8-6: Brake PRT Comparison (in seconds)**

	“Surprised”	“Expected”
Mean	1.31	0.54
Standard Deviation	0.61	0.1
50 <sup>th</sup> Percentile	1.18	0.53
85 <sup>th</sup> Percentile	1.87	0.64
95 <sup>th</sup> Percentile	2.45	0.72
99 <sup>th</sup> Percentile	3.31	0.82

The PRT of the violating vehicle ‘A’ is considered “expected” as the violator committing the illegal pass is aware of the risky consequences, where as the PRT of vehicle ‘C’ traveling in the opposing direction is taken as “surprised” because the driver is unaware of the vehicle violation.

### **8.3.3.7 Reading Time Allowance**

For signs that cannot be comprehended in one glance, i.e., word message signs, allowance must be made for reading the information and then deciding what to do, before a driver in traffic will begin to maneuver in response to the information.

Reading speed is affected by a host of factors (Boff and Lincoln 1988) such as the type of text, number of words, sentence structure, information order, purpose of reading, the method of presentation, and whatever else the driver is doing. For purposes of traffic flow modeling, however, a general rule of thumb may suffice. This can be found in Dudek (1990): "Research...has indicated that a minimum exposure time of one second per short word (four to eight characters) (*exclusive of prepositions and other similar connectors*) or two seconds per unit of information, whichever is largest, should be used for **unfamiliar drivers**. On a sign having 12 to 16 characters per line, this minimum exposure time will be two seconds per line."

"Exposure time" can also be interpreted as "reading time" and so used in estimating how long drivers will take to read and comprehend a sign with a given message. For example, a sign that is displayed below would require a minimum of 8 or up to 12 seconds if the driver is not familiar with the sign ("worst case," but able to read the sign).

**Traffic Conditions**  
**Next 2 Miles**  
**Disabled Vehicle on I-77**  
**Use I-77 Bypass Next Exit**

In Dudek's study (1990), 85 percent of drivers **familiar** with similar signs read this 13-word message (excluding prepositions) with 6 message units in 6.7 seconds (**about 0.5 second per word or 1.1 second per message unit**). However, the formulas in the literature tend to be conservative.

Based on the above, the short word sign “DO NOT PASS” proposed as a warning sign in this study, consists of two short words and one message unit, would require unfamiliar drivers from 2 to 4 seconds to be read and comprehend. However, Route 114 is a local road that serves local commuters, therefore we may consider the road commuters as familiar drivers, which could – according to Dudek’s study- read and comprehend the sign in 1 to 1.1 seconds. Consequently, an average of one-second reading time is assumed in simulating the time lag as illustrated in the following section.

#### ***8.3.3.8 Time lag Components***

A time lag accounts for the period of time starting from the moment when the vehicle crosses the double yellow line. This time lag could vary depending on the following two cases:

**Case 1:** the violating car perceives the warning message before an opposing vehicle is seen. In this case the time lag accounts for:

- 1- Verification process, that is the time required to verify a violation, and
- 2- Displaying warning message, that is the time required displaying the message.

The camera detection system needs at least three consecutive images to compare and verify pixel changes before the wrong way occurrence is confirmed. Therefore, for a video and transmission speed of 30 images per second, the central processor would require 0.1 seconds to receive the images for analysis. If a violation is verified, the system promptly closes the

circuit and activates the warning message virtually at a zero time lag. However, to be conservative we may account for another 0.1 second for image analysis and the warning display time lag. Consequently, the total time lag amounts for 0.2 seconds for the two time lag components (1+2) described above.

The other time lags to consider are:

3- Reading: a time lag of one second is assumed as illustrated in previous section.

4- Perception/ Reaction time lag

5- Movement time lag

As we have discussed earlier, the fourth and fifth time lag components combined altogether are considered randomly distributed with a mean and standard deviation of 1.31 and 0.61 seconds respectively for the “surprised” vehicle C, and 0.54 and 0.1 second for the “expected” vehicle A.

**Case 2:** The opposing vehicle is seen before reading stage. The time lag in this case accounts for the response time only. That is, we are going to consider time lag components 4 and 5 only.

### ***8.3.3.9 Driver's conditions***

Vehicle A driver's condition is an influential factor that affects driver's behavior when acting/reacting in many situations. In our case, driving under influence DUI plays a major role in determining the value of some parameters such as the time lag components described above.

The simulation will take into consideration two types of drivers:

1- Regular driving conditions.

2- Driving under influence (DUI).

The population of each type and the impact of drinking on the reaction levels will be taken from studies conducted on those issues, in addition to other sources related directly to our situation such as police accident reports.

Drugs - Alcohol abuse in isolation and combination with other drugs, legal or otherwise, has a generally deleterious effect on performance (Hulbert 1988; Smiley 1974). Performance differences vary considerably for any given driver. In general, alcohol lengthens driver reaction times and



cognitive processing times. The only drug incidence which is sufficiently large to merit consideration in traffic flow theory is alcohol.

Although incidence of alcohol involvement in *accidents* has been researched for many years, and has been found to be substantial, very little is known about incidence and levels of impairment in the driving population, other than it must also be substantial. Because these drivers are impaired, they are over-represented in accidents. Price (1988) cites estimates that 92 percent of the adult populations of the U.S. use alcohol, and perhaps 11 percent of the total adult population (20-70 years of age) has alcohol abuse problems. The National Highway Traffic Safety Administration estimates that alcohol was involved in 39 percent of fatal crashes and in 7 percent of all crashes in 1997.

Recently, NHTSA issued in August 2000 a research entitled “ Driver Characteristics and Impairment at Various BAC”. The research conducted experiments on 168 alcoholic drivers of different gender (male and females), age group (4 groups from 19 to 70 years old) and drinking practice (light, moderate and heavy).

The purpose of these experiments was to determine the magnitude of alcohol impairment of driving skills as blood alcohol content, BACs, varied from zero to 0.10%. Using a driving simulator and a divided attention task, 168 subjects were examined at BACs of up to 0.10% for moderate and heavy drinkers and up to 0.08% for light drinkers.

It was found that alcohol significantly impaired performance on some measures for all examined BACs from 0.02% to 0.10% (see table 8-7). The magnitude of the impairment increased with increasing BAC. Also, it was found that differences in the magnitude of alcohol impairment between categories of age, gender, and drinking practices were small, inconsistent in direction, and did not reach statistical significance. It is possible that significant differences would have emerged if a wider range of subject characteristics and BACs had been examined.

**Table 8-7: Performance Under Alcohol Influence**

Test	Pre-test	Blood Alcohol Content (BAC) %					
		0.10	0.08	0.06	0.04	0.02	0.00
Reaction Time (sec)	3.5	4.1	4.1	4.1	3.8	3.6	3.4
Correct Responses (no.)	47	41	42	44	45	46	46
# Of Collisions (no.)	4		9	9	8	6	4
Times Over Speed (no.)	4		12	11	11	9	8

Because no data were available on the alcohol levels of drivers driving along the study section of Route 114, a number of assumptions were made, as follow:

- 1- Twenty percent of the violators were assumed to drive under the alcohol influence. This assumption is based on the accidents data, which showed that 20% of the crashes involved alcohol.
- 2- When simulating violations, drivers of vehicles B and C were assumed to operate under normal conditions, although they could be impaired to some degree by alcohol.
- 3- For impaired drivers, 0.5 second was added to the driver’s lag time in terms of reading and PRT.

#### **8.4 Simulation Methodology**

The simulation is a powerful tool that enables the user to:

- A- verify the system functioning and performance, and
- B- conduct evaluation of the system effectiveness in reducing collision risks.

The simulation is validated by comparing the rate of collisions obtained from simulation to that of the real world differentiated for both cases:

- 1- “Without“ the warning system (base case), and
- 2- “With” the warning system (improvement case)

Figures 8-11 and 8-12 depict the logic behind the simulation of the system functions without and with the proposed detection and warning system. The logic consists of tracking the three vehicles, as follows:

**Direction 1:** deals mainly with vehicle A sequence of events attempting to start and complete the takeover maneuver. Vehicle B is assumed to be unaware of vehicle A's act, hence, the vehicle continues to travel at the same speed throughout the entire simulation.

**Direction 2:** deals with vehicle C, the vehicle approaching in the opposing direction and the second potential victim of the head-on collision. Similar to vehicle A, the location of vehicle C is tracked mainly to assess when its driver will see vehicle A. At the moment the driver of vehicle C driver establishes a visual contact with vehicle A, the driver takes necessary action to avoid a collision.

**Time:** This dependent variable will be introduced in every kinematic equation describing the location, speed and acceleration of the various vehicles. The periodic scanning method will be used in the simulation, where all time dependent variables are updated at 0.1 seconds increments.

As the flowcharts also show, the outcome of the takeover maneuver could be either a safe passing or an unavoidable crash depending on vehicle A driver's reaction and action decision.

#### **8.4.1 "Without" warning system case**

"Without" is the base case on which we are going to validate the effectiveness of the simulation. Actually, the kind of parameters introduced in the simulation and the sequence of processes should explain to large extent what is happening in reality. Therefore, we expect that the simulation outcome of the "without" case should reflect the current situation to an acceptable degree of realism.

Figure 8-11 depicts the simulation flowchart for passing "without" the warning system. After we generating randomly the speeds and the locations of the three vehicles, we examine the passing threshold. A loop was created representing the process of continuous monitoring of the opposite direction that the violating driver performs, as long as the driver of vehicle A is in the passing phase. This loop updates the different parameters every 0.1 second until an opposing vehicle C is seen or the passing maneuver is completed.

Once the vehicles see each other, random PRT time lag periods for both vehicles start, after which vehicle C decelerates whereas vehicle A could accelerate or decelerate depending on the action that the violator would take. Different scenarios of those possible actions will be discussed in detailed in a coming section.

#### **8.4.2 “With” warning system case**

Generally, the “ with warning system” case follows the same logic as the “without case”.

However, it is more complicated because the drivers would act differently depending on which event might occur first: vehicles A and C see each other or the violation is detected.

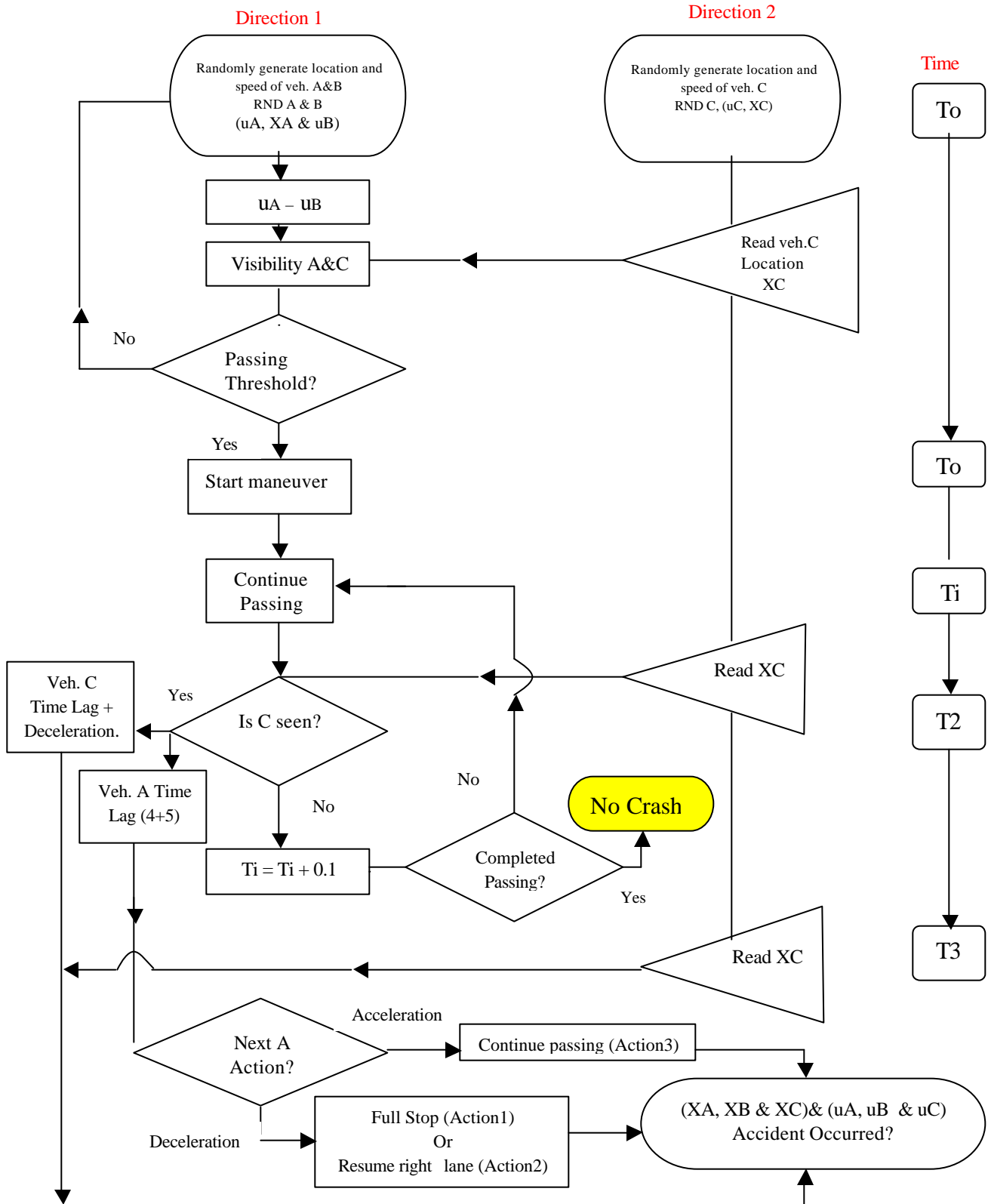
For the first situation when A and C see each other, both start their PRT time lag at the same moment similar to the without case.

For the second situation when the system detects the violation and warns the driver of vehicle A, only vehicle A starts its time lag period. This period consists of reading time in addition to the PRT. Meanwhile, vehicle C is unaware of the violation. It will keep its speedy motion until it sees vehicle A after which it starts its PRT followed by the deceleration action.

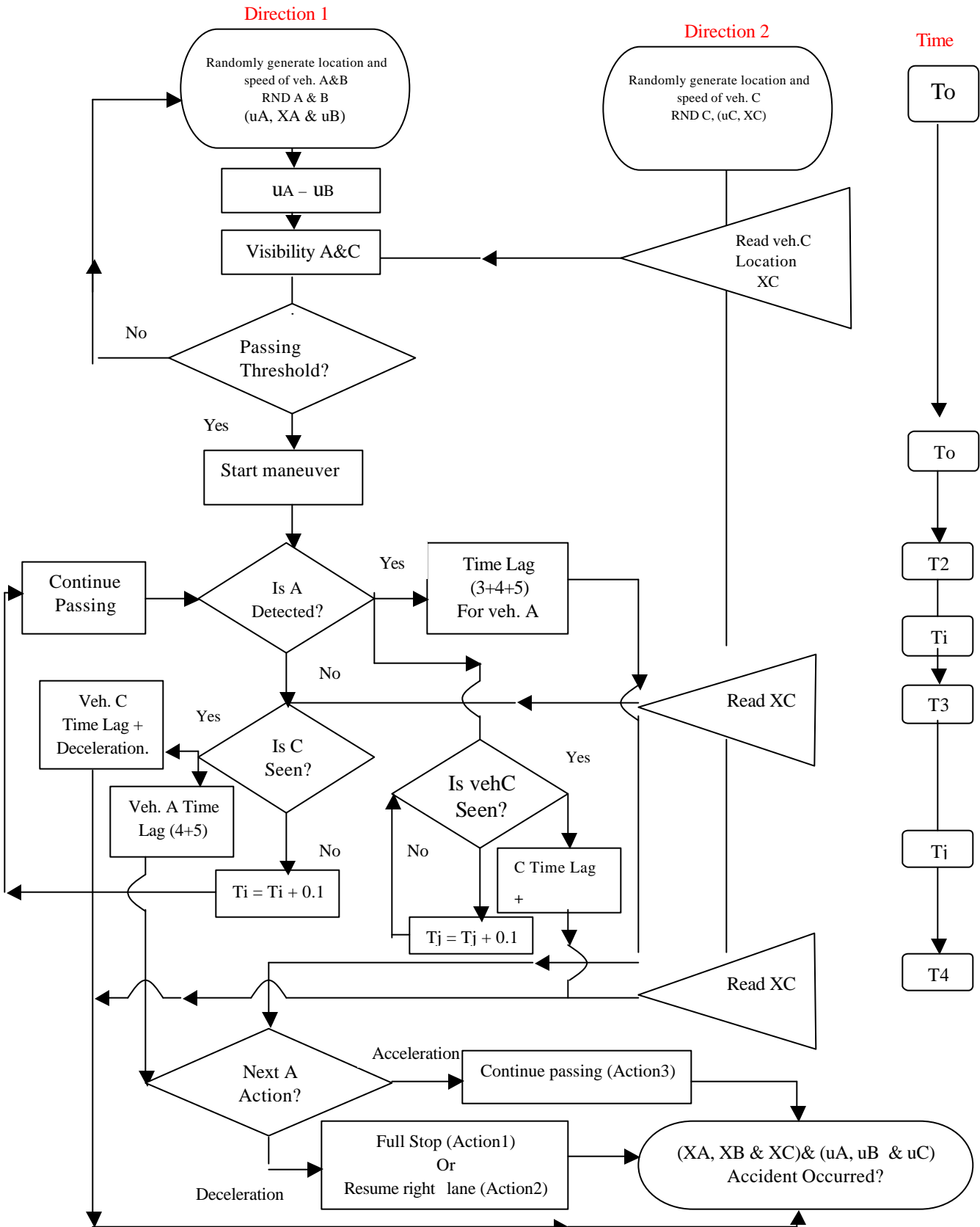
Whether a line of sight is established or warning is displayed, vehicle A could brake or accelerate depending on the action taken by the violator. Similar to the “without” case, different action scenarios of the possible actions will be analyzed.

Figure 8-12 depicts the simulation flowchart for passing “with” warning system case.

**Figure 8-11: Passing Violation Without the Warning System**



**Figure 8-12: Passing Violation with Warning System**



### 8.4.3 Post Perception Action

Based on the above, two perception situations could be specified and exposed to driver A while in the left lane violating the solid yellow line:

- 1- Either perceiving the fact that a car C is coming in the opposite direction, and he must do something to avoid collision. Or,
- 2- Perceiving the fact that he was “caught” by the detection system and he must obey and go back to the right lane.

While the first situation might take place in the both “with” and “without” warning system cases, the second could happen only when the system is installed and put in service, that is in the “with” case.

Here we should have a little pose to visualize what kind of decision or action the driver A may take in either situation. An unlimited number of “logical” actions may occur, arising principally from the uncertainty in human behavior. Different individuals would perform different actions when exposed to different physical and psychological conditions (surprise, fear, anxiety, drinking problem, life pressures, etc). And this per se could be a vast and interesting field for human factor researchers to examine and study such human behavior during accident occurrence.

Anyway, for the sake of simplifying such complex situation, we will assume in our simulation the following scenarios:

- **Vehicle B will remain in its lane at constant speed.** Here, we assume that vehicle B driver will stay neutral towards the illegal passing maneuver of A, and avoid taking actions such as accelerating (to tease the driver of vehicle A or forbid him to takeover) or decelerating (to help driver A complete a safe pass and merge action). Or simply, we can assume that driver B is unaware of what is happening around him.
- **Driver C will decelerate when Vehicles A and C are revealed to each other without leaving the lane.** This assumption is partially valid in our case because of the

lack of shoulder. Some drivers, however, may unconsciously prefer to run out the road away from a perceived crash. Anyway, that could also mean that a crash in a way has occurred, but it would be classified under a crash type other than a head-on accident.

- **For driver A action, we may distinguish two situations:**

**Situation 1: The two opposing vehicles A&C see each other:** This event could take place in both the “with” and “without” case analysis. Driver A could choose to make one of three assumed actions, perceived by him as the appropriate one, to avoid a possible collision with C. These three actions are:

**1- Make a complete stop.** Driver A will decelerate assuming that a full stop would be most likely achievable before he collides with C. In this case the conditions to avoid a crash are:

$$\text{distance AC} > 0 \rightarrow d - (X_{At} + X_{Ct}) > 0 \quad \text{at time } t \text{ when}$$

$$u_{At} = 0 \text{ and } u_{Ct} = 0.$$

Where:  $X_{At}$ ,  $X_{Ct}$  = the locations of vehicles A and C at time t

$u_{At}$ ,  $u_{Ct}$  = the velocities of vehicles A and C at time t

$d$  = the length of the road link under detection

**2- Set back and move to the right lane.** Here driver A assumes that he/she has enough time to start decelerating while making a lane change to the right behind vehicle B in order to avoid collision with vehicle C. To observe such a happy outcome, the following conditions must be fulfilled:

$$X_{At} < X_{Bt} - E_s \quad \text{at time } t \text{ when}$$

$$X_{At} + X_{Ct} = d$$

Where:  $E_s$  = **emergency headway** that vehicle A needs to have behind vehicle B to avoid collision with it.

Referring to the Microscopic Traffic SIMulator (MITSIM) developed by Yang and Koutsopoulos (1996), under the “emergency regime”, the following vehicle A uses



appropriate deceleration rate to avoid collision with B. The model suggested to fulfill such requirement is:

$$a_A = \min \left\{ \bar{a}_A; a_B - 0.5(u_A - u_B)^2 / g \right\} \quad u_A > u_B \quad \text{Where:}$$

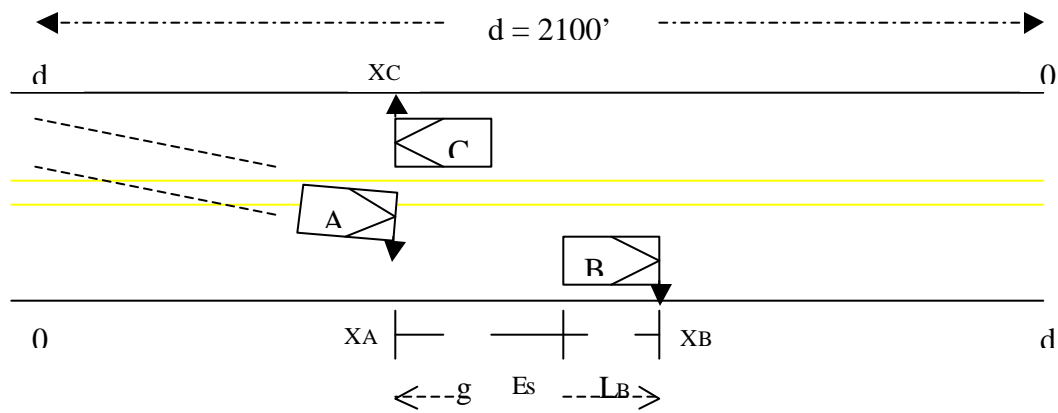
$a_A, a_B$  = Acceleration (deceleration when negative) rates of vehicles A&B

$\bar{a}_A$  = Normal deceleration rate of vehicle A

$u_A, u_B$  = Speed of vehicles A and B

$g$  = Clearing distance separating vehicles A and B

Figure 8-13 depicts the positions of the three vehicles at time t when A and C are about to collide.



**Figure 8-13: Vehicle A Merging Under Emergency Regime Behind B**

As B is running at constant speed, it has zero acceleration. Considering the emergency braking that would result in a more aggressive deceleration, we may conclude:

$$a_A = -0.5(u_A - u_B)^2 / g$$

$$\rightarrow g = -0.5(u_A - u_B)^2 / a_A = -1.076(\Delta u)^2 / a_A \quad (\text{g in feet, } u \text{ in mph})$$

The case described above fits when vehicles A and C see each other after A starts the violation at a higher speed than B, but before it overtakes B.

Another case could happen when vehicles A and C see each other after A starts the violation and overtakes B. In this case A should decelerates to a speed less than B

then try to merge behind B before it hits vehicle C. Here we are going to assume that can take place when at the moment of merging, the speed of A is less at least by 5mph than B and the minimum emergency distance  $g$  is 10 feet.

Finally,  $E_s$  the headway required to avoid crash between A and B is given by

$$E_s = g + L_B \quad \text{where } L_B = \text{length of vehicle B.}$$

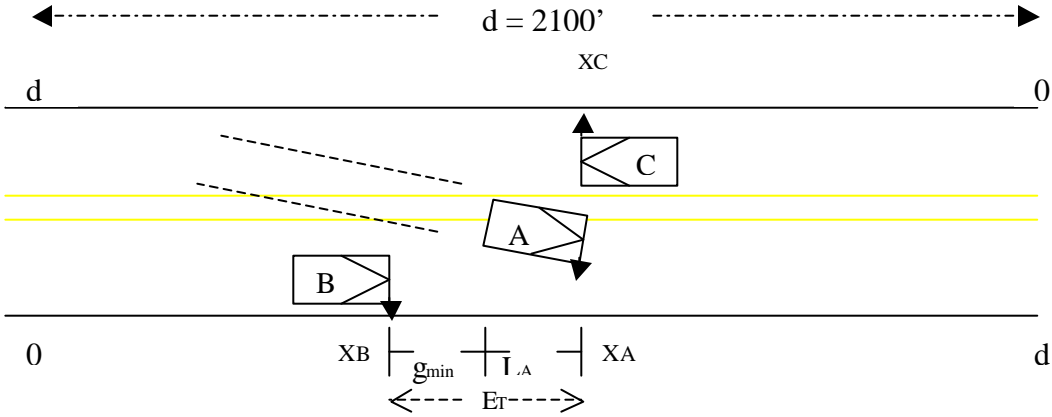
**3- Continue the passing maneuver in an attempt to avoid collision with vehicle C.** Driver A will insist to overpass B by continuing accelerating under the assumption that he/she is capable to complete a safe passing before he collides with the decelerating vehicle C. In order to accomplish that, driver A will overtake vehicle B by a minimum emergency distance  $E_T$  before he/she makes his/her fast lane change to the right ahead of vehicle B (see figure 8-14). Also to observe such a scenario, the following conditions are to be fulfilled:

$$X_{At} > X_{Bt} + E_T \quad \text{at time } t \text{ when}$$

$$X_{At} + X_{Ct} = d$$

Where:

$E_T$  = the minimum headway that A needs to have ahead of B to make safe lane change.



**Figure 8-14: Vehicle A Merging Under Emergency Regime Ahead of B**

As the speed of vehicle A is higher than that of B,  $E_T$  could be estimated by the following simple equation:

$$E_T = g_{\min} + L_A$$

where:

$g_{\min}$  = minimum distance set for A to make safe merging ahead of B, taken equal to 10 feet.

$L_A$  = length of vehicle A.

**Situation 2: Driver A perceives that his/her violation was detected by the system.**

This situation could happen only in the “With” case. The driver can take also any of the three actions described above. However, we will suppose that all drivers under the influence of the displaying warning message, will mostly obey and respond immediately after perceiving the warning by decelerating and resuming their right lane (action 2). This action actually could be – to a large extent – realistic, taking into consideration the psychological effect of the flashing lights and the impact of the strong warning message.

Anyway, the other actions will be analyzed too, in order to compare their outcomes with that of the supposed action.

#### **8.4.4 Initialized and generated variables**

The variables to be included in the simulation could be classified into two types:

- 1- Initialized variables (or input variables) that need to be quantified before being inserted. They are site and case specific variables that differ from one project analysis to another. Such variables could characterize the road geometry (grade, road length) or the traffic (average headway, initial speed, violation rate, ..etc).
  
- 2- Generated variables that are produced during the analysis runs. They could be of intermediate or transitory nature like the acceleration and the location of the vehicles, or of final (or output) variables nature like number of crashes by type of action and vehicle speed at collision moment.

Tables 8-8, 8-9, and 8-10 illustrate the types of some main variables introduced in either “with” or “without” simulation cases or both, with their symbols. They are arranged as vehicle-related, driver-related and road-related variables.

**Table 8-8: Vehicle- Related Variables**

Variable	Symbol	Variable Description	Case Analysis		Variable Type	
			With	Without	Input	Generated
Vehicle ID	A, B, C	The three vehicles involved in the collision occurrence.	X	X	X	
Vehicle Class	LV MV HV	Type of vehicle that implies its characteristics in terms of vehicle length, speed and acceleration ranges.	X X X	X X X		X X X
Vehicle Length	LV_length MV_length	Specifies the length of vehicle depending on its class.	X X	X X	X X	
Driver's eye Height	LV_eye MV_eye	Specifies the vehicle driver's eyeheight depending on its class.	X X	X X	X X	
Top Vehicle Height	LV_height MV_height HV_height	Specifies the vehicle top height depending on its class..	X X X	X X X	X X X	
Vehicle Location	xvehi	The abscissa of vehicle i	X	X		X
Vehicle Speed	Vehi_sim_sp vehi_ini_sp vehA_Max_s	Speed of vehicle i at time t The initial speed of the trial. Speed limit of vehicle A	X X X	X X X		X X X
Vehicle Acceleration	vehA_acc (t)	The acceleration of vehicle A at moment t .	X	X		X
Vehicle Deceleration	vehi_decel (t)	The deceleration of vehicle i at moment t.	X	X		X
Speed Thresholds	min_sp_threshold max_sp_threshold sp_threshold	minimum ,maximum and generated speed difference thresholds between A and B.	X X X	X X X	X X	
Traffic Volume	qvehA qvehC	The traffic flow volumes (vph) for direction of vehicle A and C.	X X	X X		X X
Minimum dispatching distance	min_distAtoB	The minimum distance between A and B at t = 0 before A starts its violation	X	X		X
Distance from AtoB Distance from AtoC	dist_AB dist_AC	Distance separating the two vehicles at time t	X X	X X		X X
Safe Merging distances	emerg_overtake emerg_setback	Minimum distance for A to make safe merging ahead of B or behind it	X X	X X		X X

**Table 8-9: Driver- Related Variables**

Variable	Symbol	Variable Description	Case Analysis		Variable Type	
			With	Without	Input	Generated
Violation rate	East_viol	The annual number of violation committed by A	X	X	X	
	West_viol		X	X	X	
Time Lag (verification, reading, perception and reaction)	timelag_attributes	Time lag components	X	X		X
	timelag_12	Time lag to verify violation	X	X		X
	timelag345	Time lag that driver needs for reading and PRT	X	X		X
Driver's Braking Behavior	brake_attributes	Determine drivers A and C braking behavior when they want to decelerates	X	X		X
PRT of C	t_C_prt_index	The time index when driver C ends his PRT time lag (case when A after it detected.	X			X
Driving Under Influence	DUI_perc	The percent of violating drivers under influence of alcohol.	X	X	X	
	DUI	0 or 1 to indicate whether or not violator is a DUI case	X	X		X

**Table 8-10: Roadway- Related Variables**

Variable	Symbol	Variable Description	Case Analysis		Variable Type	
			With	Without	Input	Generated
Road profile Attributes	x_E , x_W	Horizontal projection of the road	X	X	X	
	z_E , z_W	Vertical projection of the road	X	X	X	
	gr_E, gr_W	Grade of road sub-segments	X	X	X	
Road Length	d	The length of the road link curve put under detection.	X	X	X	
Grade at Vehicle A Location	grade_A	The grade of road at the point where A is located at time t	X	X		X
Violation Detection	t_detect_index	The time index when the violation is detected by the system before A and C see each other	X			X
Visibility (with case)	t_C_see_index	The time index when driver C sees A after it was detected	X		X	
Visibility (without case)	t_see_index	The time index when drivers of A and C see each other.	X	X	X	

## 8.5 Simulation Runs Output

Every violation in any simulation run output consists of a series of matrices describing the time-dependent parameters while the violation process is progressing. Some of the main parameters are the locations and speeds of the three vehicles A, B and C, the acceleration and deceleration of vehicles A and C, and the visibility and detection status for vehicles A and C.

All these parameters (and others of less important role) are updated every 0.1 second throughout the simulation period of one violation considered here of 25 seconds. Knowing that one run simulates 890 violations, which are the real-world estimated annual number of violations having short passing distance in both directions. Since we have 3 action scenarios to apply in the "with" and "without" cases, we come up finally with  $2 \times 3 \times 890 \times 251$  data fields to show for every time-dependent parameter. The resulting output would be 52 megabytes in size for each one year run output file.

One practical way to follow up the progress of violations could be by presenting the data in form of curves that exhibit the various varying parameters. The examination of these curves allows us to understand the development of the violation process. It also allows verifying the impact of the detection and warning system on the final outcome, as well as the effect of changing one input parameter during the sensitivity analysis.

### 8.5.1 Presenting the Results of a Violation

The results of a violation could be described by four superimposing figures. These figures are:

- 1- The time when a visibility between vehicles A and C is established, and when the violating car A is detected, whichever comes first.
- 2- The acceleration (or deceleration) curves of vehicles A and C.
- 3- The speed curves of vehicles A, B and C.
- 4- The locations curves of the three vehicles and the curve showing the distance between vehicles A and C.

**These figures should be read from bottom to top.** They offer consistent information in describing the various steps in the development of a violation. First we can see the point of time at which the line of sight is established between A and C drivers (in the “without the

system” case) or verify whether a detection was established by the system before that (in the “with the system” case). Then we can verify the perception-reaction time lag before the vehicle C starts deceleration. Also we can verify the development of vehicle A action (1 out of 3) on the final outcome of the violation, whether a head-on collision is going to occur or not.

The next pages show a sample of different violations with different conditions, attributes and outcomes:

- Figure 8-15 exhibits the progression of a violation taken from the “without system” analysis, where A performed action 1 (attempt to make full stop) that ended unsuccessfully by colliding with C.
- Figure 8-16 exhibits the progression of a violation taken from the “with system” analysis, where A performed action 1 as it perceived the early warning, and ended up successfully where collision with C was avoided.
- Figure 8-17 exhibits the progression of a violation taken from the “without system” analysis, where A performed action 2 (set back behind B) that ended successfully with no collision with C.
- Figure 8-18 exhibits the progression of a violation taken from the “with system” analysis, where A performed action 2 even before vehicle C driver’s noticed what happened.
- Figure 8-19 presents the progression of a violation taken from the “without system” analysis, where A performed action 3 (insist to take over B) that ended up with a collision with C.



**Example: 1**

**System Analysis Case: "Without"**

**Vehicle A Driver's Action: Action1**

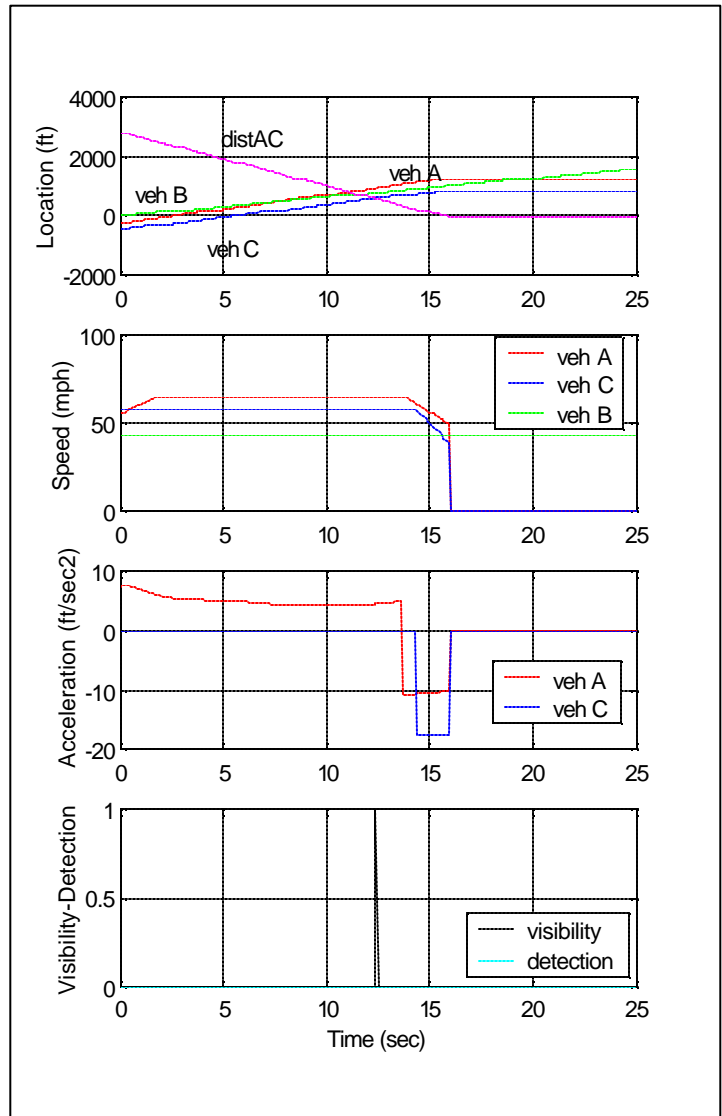
**(N.B. Read the figures upward)**

Location graph: Vehicle A was just taking over B when it saw C. at that moment distance AC was around 550 feet, a distance that was not enough for both vehicles to make safe full stop. The maneuver ended up with a collision (dist AC curve reached zero)

Speed graph: Vehicle A increased speed up to the maximum limit (65mph), and continued at constant speed like vehicles B and C. Speeds of A and C started decreasing at the moment when they exercised brake action. When the collision occurred both speeds dropped to zero.

Acceleration graph: After PRT periods for both vehicles A and C drivers, both vehicles decelerated to make full stop. (PRT of C is longer than A's, that is, C response was slower than A).

Stimulus graph: A line of sight is established between vehicles A and C at around 12.5 second.



**Figure 8-15: Sample Of a Simulation Output (Without/Action1)**

## Example: 2

**System Analysis Case:** "With"

**Vehicle A Driver's Action:** Action1

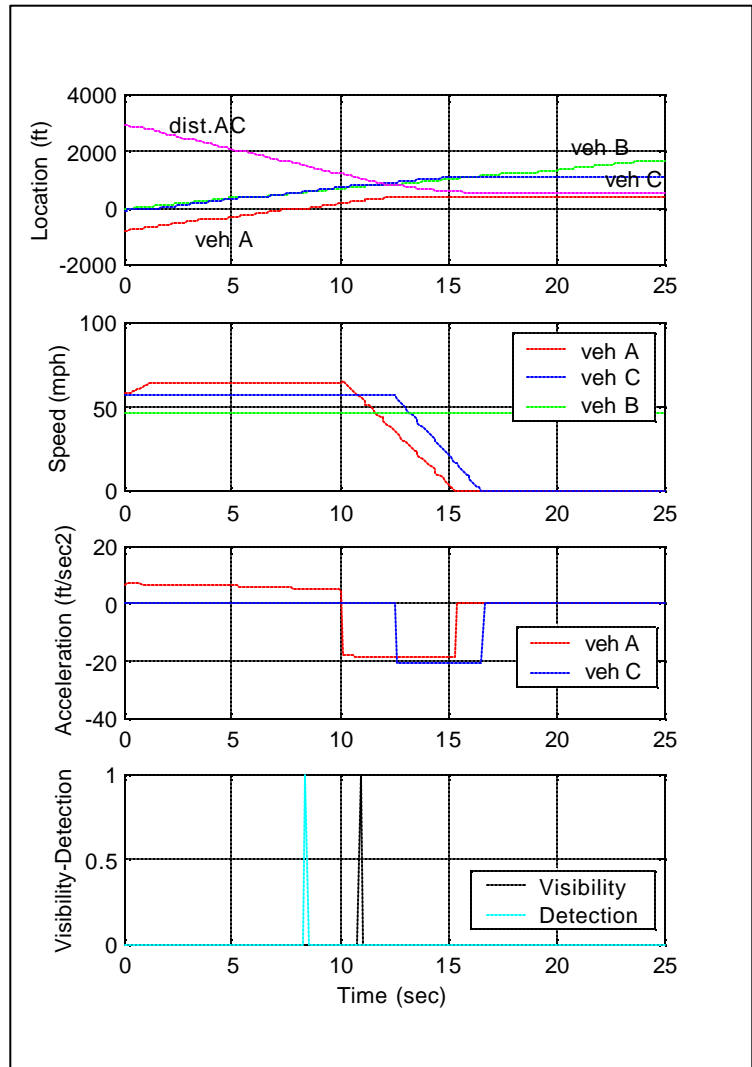
Location graph: Vehicle A was not able to take over B because of the warning. At that moment distance AC was long enough for both vehicles to make full stop without collision (distance AC curve is above zero)

Speed graph: Vehicle A raised speed up to the 65 mph maximum limit, then continued at constant speed. Both A and C started decreasing their speed at the moment when they exercised brake action, while B continued at constant speed.

Acceleration graph: After its PRT period, vehicle A started deceleration to make full stop. C drivers started the same action as he perceived vehicle A coming in the opposite direction.

Stimulus graph: The system detected and warned A at around 8<sup>th</sup> second earlier than vehicles A and C saw each other at 11 second.

**NB.** In cases where vehicles A and C see each other before the system warning is launched, drivers behavior will be similar to that shown in example 1.



**Figure 8-16: Sample Of a Simulation Output (With/Action1)**

**Example: 3**

**System Analysis Case: "Without"**

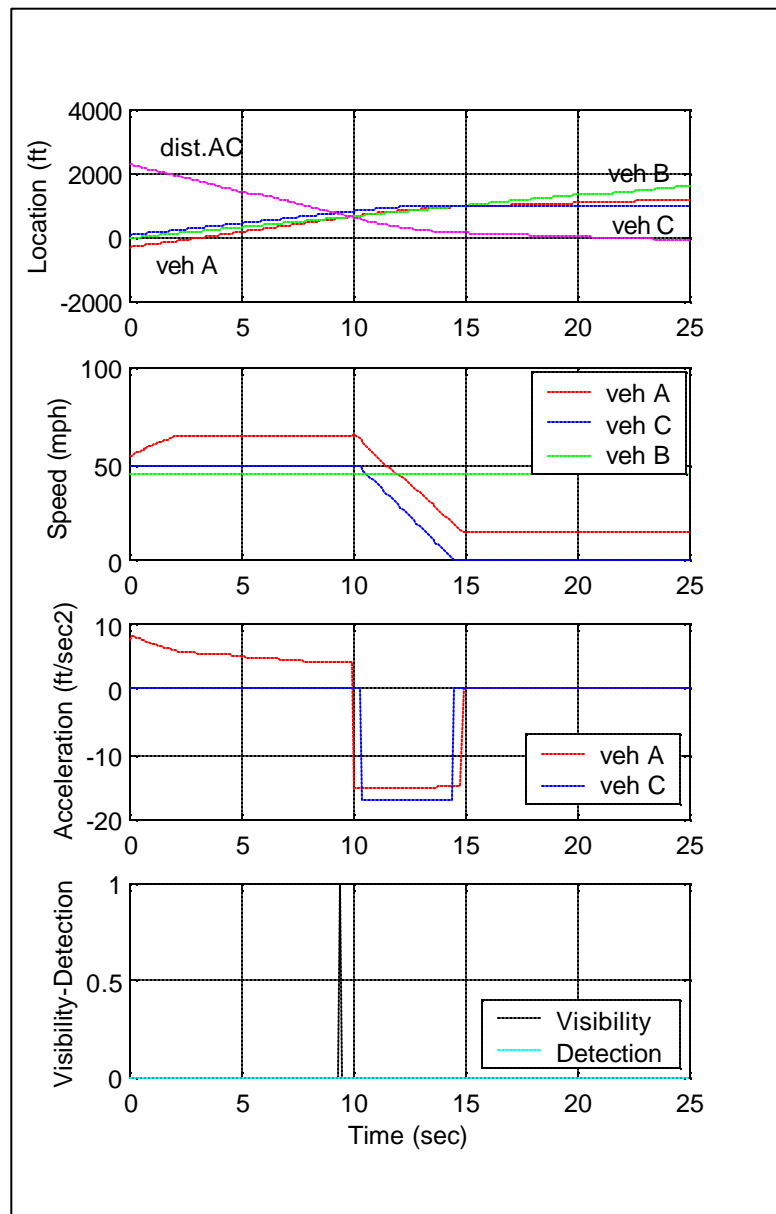
**Vehicle A Driver's Action: Action2**

Location graph: Vehicle A almost taking over B when it saw C. driver A slowed and setback behind vehicle A successfully at 15<sup>th</sup> second with no collision (dist AC curve is above zero at that moment).

Speed graph: Vehicle A raised speed up to the maximum speed to start passing maneuver, then continued at constant speed. A started decreasing its speed till it became again behind B at a distance enough to make merging into the right lane. After that it continue at constant speed.

Acceleration graph: After its PRT period, vehicle A started deceleration to setback behind B and that took around 5 seconds. Vehicle C driver decelerated as he perceived vehicle A coming in the opposite direction and made full stop.

Stimulus graph: Vehicles A and C saw each other around the 9<sup>th</sup> second. After a PRT period A will try to setback behind B while C will decelerate and make full stop.



**Figure 8-17: Sample Of a Simulation Output (Without/Action2)**

**Example: 4**

**System Analysis Case: "With"**

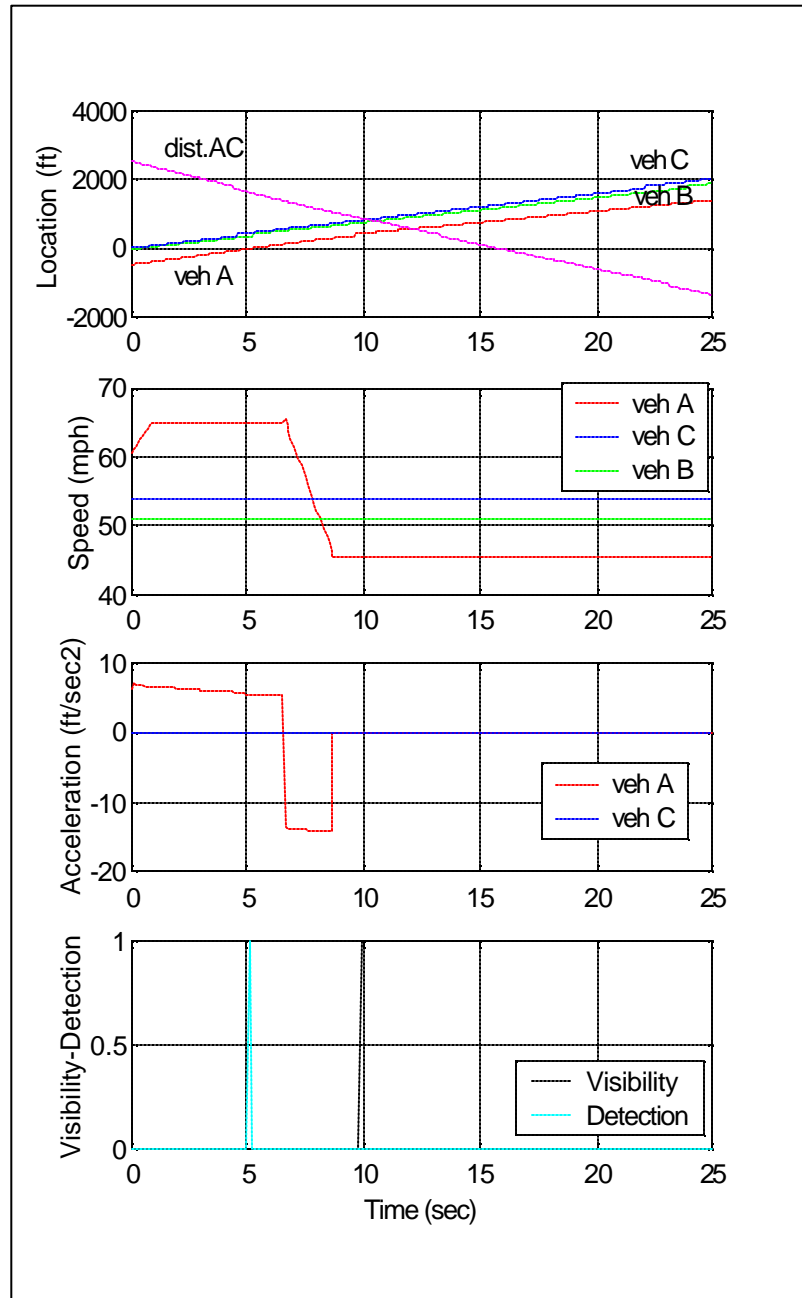
**Vehicle A Driver's Action: Action2**

Location graph: Vehicle A was trying to minimize the distance with B but it couldn't because of the warning. As A set back behind B the distance between them started to increase again. At the moment when distance AC reached the zero value (around 16<sup>th</sup> second), vehicle A by that time had already been setback and resumed its position behind B (at moment 8.7 seconds)

Speed graph: Vehicle A raised speed up to the maximum limit considered to perform the passing maneuver, then continued at constant speed. As driver A perceived the warning, he slowed down to a speed less than that of vehicle B and merged to the right. As driver C didn't notice vehicle A action, he/she continued at the original speed

Acceleration graph: After its PRT period, vehicle A started deceleration to set back behind B at constant speed. that had been accomplished in less than 3 seconds even before C could noticed what happened. In this case C continued its path at constant speed (acceleration equal to zero).

Stimulus graph: The system detected and warned A at around 5<sup>th</sup> second earlier than vehicles A and C saw each other around the 10<sup>th</sup> second.



**Figure 8-18: Sample Of a Simulation Output (With/Action2)**

**Example: 5**

**System Analysis Case: "With"**

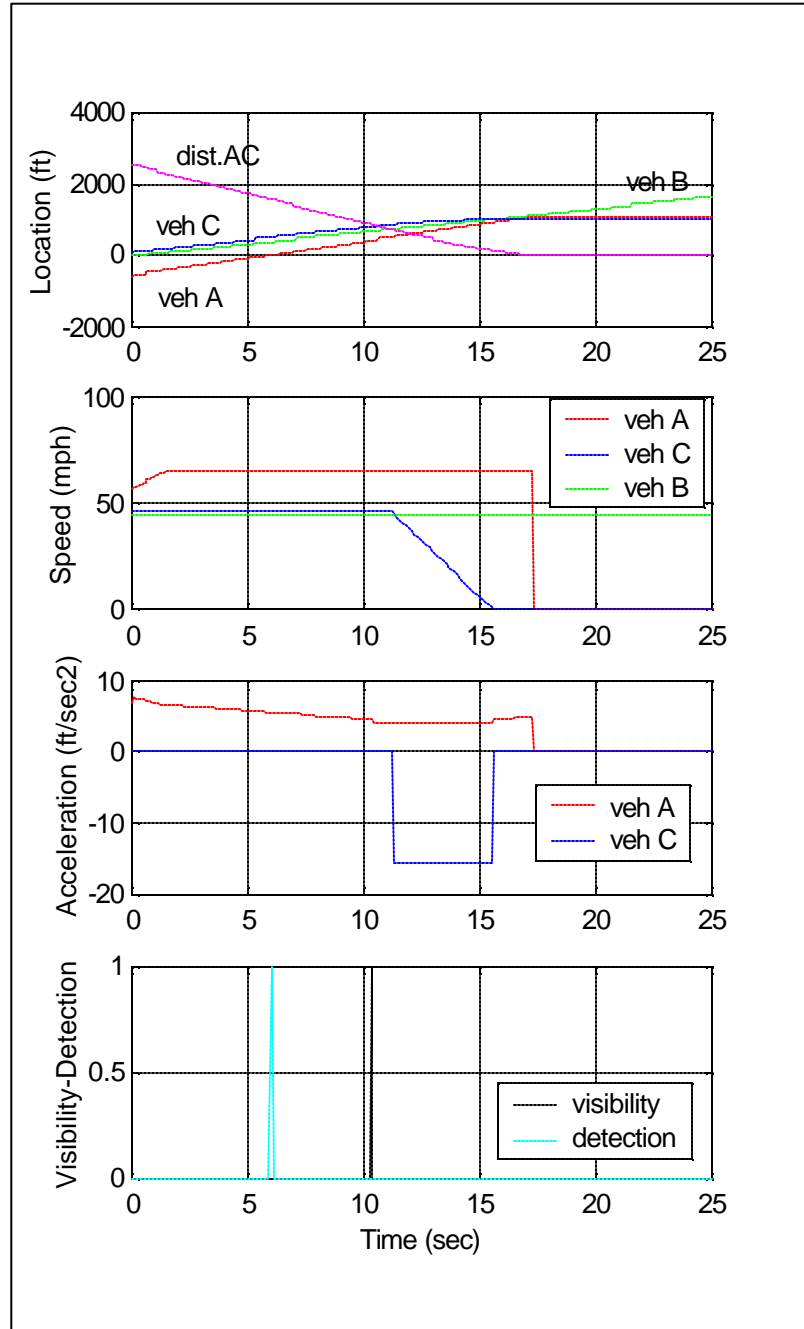
**Vehicle A Driver's Action: Action3**

Location graph: Vehicle A was trying to take over B when it received warning at the 6<sup>th</sup> second. At that moment distance AC was around 1500 feet, a distance that was not enough for vehicle A to continue and make safe passing before it hit vehicle C. Unfortunately, vehicle A continued the maneuver and ended up with a collision (dist AC curve reached zero) at 17<sup>th</sup> second.

Speed graph: Vehicle A increased speed up to the maximum limit (65mph), and continued at the same speed even after the driver perceived the warning message. Vehicle C driver started decreasing speed after he perceived the oncoming vehicle A and made full stop at around 16<sup>th</sup> second. When the collision occurred the speed of A dropped to zero.

Acceleration graph: After PRT period vehicle A driver did not take any action to slow down. In the contrary, he insisted to continue his illegal passing at the maximum speed while vehicle C driver decelerated to make full stop.

Stimulus graph: The system detected and warned A at around 6<sup>th</sup> second earlier than vehicles A and C saw each other around the 11<sup>th</sup> second.



**Figure 8-19: Sample Of a Simulation Output (With/Action3)**

Having examined the examples above, we may note the following:

- 1- The slope of the speed curves shown in the speed plots reflect the acceleration rate depicted in the acceleration plot just below, taking into consideration that the speed of A can not pass a certain maximum limit that was determined based on the field data observed.
- 2- The low acceleration variation of vehicle A reflects the changes in grades and speed when the latter is below the maximum speed limit.
- 3- Vehicle C driver's behavior is affected only by the stimulus of visibility, whereas the driver of vehicle A is affected either by the visibility once established or by the detection and warning stimulus, whichever comes first.
- 4- The system has no influence on the violation progression when vehicles A and C drivers see each other. In this case, similar to the "without case", both drivers start their actions following that stimulus.
- 5- Finally, the system also has no influence on the outcome of the violation as long as the driver does not obey the warning sign and insists on continuing the maneuver.

The subsequent chapter provides a in-depth sensitivity analysis of the system performance.