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By Anagha Gurunath Modak

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For the degree of Master of Science in Electrical and Computer Engineering

Is approved by the final examining committee:

1. Sarah Koskie
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2. Yaobin Chen

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ROAD ACCIDENT RECONSTRUCTION AND SIMULATION WITH AND WITHOUT EDR DATA

A Thesis

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To the memory of my late father

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The omnipresent God for giving me the strength to complete this work.

PREFACE

The reason for writing this thesis is to provide guidance in the area of Event Data Recorder and HVE simulation software. The EDR, an emerging concept for road accident reconstruction, records certain crash parameters at the time of an accident. HVE is a software, provided by Engineering Dynamics Corporation, which offers a number of different simulation methods used for different real-life scenarios.

The audience of this thesis will be anyone who is interested in performing accident simulation using HVE, based on conventional reconstruction methods as well as recent EDR technology.

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LIST OF SYMBOLS

a	acceleration
f	drag factor
g	gravitational acceleration
m	mass
v_b	pre-impact velocity of the bus
v_c	pre-impact velocity of the car
v_e	end velocity
v_i	initial velocity
w_b	weight of the bus
w_c	weight of the car

LIST OF ABBREVIATIONS

ABS	Anti-lock Brake Control System
Delta-V	Change in Velocity
ECM	Electronic Control Module
EDC	Engineering Dynamics Corporation
EDCRASH	Engineering Dynamics Corporation Reconstruction of Accident Speeds on the Highway
EDGEN	Engineering Dynamics Corporation GENeral Analysis Tool
EDHIS	Engineering Dynamics Corporation Human Impact Simulator
EDR	Event Data Recorder
EDSMAC4	Engineering Dynamics Corporation Simulation Model of Automobile Collisions
EDVDB	Engineering Dynamics Vehicle Data Base
EDVDS	Engineering Dynamics Vehicle Simulation Model
EDVSM	Engineering Dynamics Vehicle Simulation Model
GATB	Graphical Articulated Total Body
HVE	Human Vehicle Environment
NHTSA	National Highway Traffic Safety Administration
OEM	Original Equipment Manufacturer
RCM	Restraint Control Module
SDM	Sensing and Diagnostic Module
SIMON	SImulation MOdel Non-linear

ABSTRACT

Modak, Anagha G. M.S.E.C.E., Purdue University, August 2011. Road Accident Reconstruction and Simulation With and Without EDR Data. Major Professor: Sarah Koskie, Ph.D.

Road accident reconstruction and simulation investigates the accident causes, suggests improvements in vehicle design and investigates failures in vehicle control and safety systems such as the anti-lock brake system (ABS) and air-bag deployment.

This thesis focuses on analysis of crash data from vehicles not equipped with collision warning systems. Vehicle parameters before and during an accident can be recorded using an Event Data Recorder (EDR) which helps in reconstructing an accident. This tool, installed in the vehicle, records different crash parameters like vehicle speed, lateral and longitudinal acceleration, seat-belt status, and air-bag deployment over a period that spens the accident. This thesis focuses on accident reconstruction with and without EDR data. A simulation software tool called HVE is used to visually recreate the reconstructed accidents. HVE is a platform to execute different accident simulation methods which are used for specific types of simulations. Two such simulation methods, EDSMAC4 and EDHIS, are discussed in this thesis. The former is an important method for vehicle-to-vehicle collisions and the latter is used for analysis of human behavior involved in the accident.

Three real-life accidents were chosen for reconstruction and simulation. They were Bus and Car accident, Three Vehicle accident and Intersection accident. These particular accidents were chosen to represent a diverse selection of accidents based on the following parameters: the locations of the accidents, the vehicles involved in each accident, and the data available. A qualitative analysis of vehicle occupant's behavior is also presented for one of the three accidents. The thesis discusses in detail the reconstruction of these three accidents. Throughout these simulations, the thesis illustrates the advantages and limitations of the EDR and HVE simulation software for accident reconstruction and simulation.

1. INTRODUCTION

Accident reconstruction is a technical process of analyzing and calculating physical parameters, such as impact velocity and damage profiles, associated with vehicles involved in an accident. This information can be used for accident-cause analysis and visual simulation.

Accident simulation is a virtual recreation of a real-life accident in order to study various aspects such as vehicle deformation, occupant injury and the capability of a vehicle to protect the occupants and pedestrians during collision.

The Event Data Recorder (EDR) is an important tool which is now being used for accident reconstruction. The EDR is a part of the Power-train Control Module (PCM) in passenger cars and the Electronic Control Module (ECM) in heavy duty vehicles. It captures specific crash parameters, some time prior to and during impact. Thus the EDR provides real-life, physical parameters associated with a vehicle at the time of a crash. The data recorded by the EDR contains diverse information such as "Last Stop Record," "Hard Brake," and "Trip Activity." The EDR has significant importance ranging from assisting in the accident reconstruction to solving vehicle safety problems.

The software used to validate technical opinions of an accident reconstruction is called HVE (Human Vehicle Environment) which is created by the company EDC (Electronic Dynamics Corporation). It is a computer environment used to study interactions among humans, vehicles, and their environments. It consists of three parts: "Input Editors," used for creation of humans, vehicles, and environment; "Event Editor," used for actual visual simulation of an accident; and "Output or Playback Editor," used for analysis of damage data, accident history, driver data, and environment data. HVE consists of different calculation methods based on the application.

For example, the EDSMAC4 (Engineering Dynamics Corporation Simulation Model of Automobile Collisions) calculation method is used for vehicle-to-vehicle accident and the EDHIS (Engineering Dynamics Corporation Human Impact Simulator) calculation method is used for simulating the human response to an impact.

1.1 Previous Work

Analysis of data recorded in the EDR and simulation in the HVE software using this data are the main areas of focus of this thesis. Hence, this section presents the previous work performed in testing validity and reliability of both the EDR data as well as the HVE simulation software.

Different manufacturers have given various names to the EDR. For example, GM's EDR is called the Sensing and Diagnostic Module (SDM) while Ford's EDR is known as the Restraint Control Module (RCM).

The primary aim in any accident reconstruction is to determine delta-V, which is the change in velocity of the vehicle before and after impact. Delta-V is a measure of severity of an accident. The EDR has the ability to record speed changes of a vehicle over time. Thus, it gives the delta-V directly. A lot of research has been done for the EDR validation, for example see Correia et al. 2001 [1], German et al. 2001 [2], Gabler; Hampton and Hinch 2004 [3], Gabler et al. TRB report 2004 [4], Gabauer and Gabler 2006 [5], and Guzek 2010 [6].

The HVE simulation platform was introduced in 1993 [7]. Several simulation methods can be run on this platform. The simulation methods used in the thesis are EDSMAC4 and EDHIS. The first method is the improved version of the EDSMAC simulation method. The validation of the EDSMAC physics model in HVE had been done by performing entire vehicle tests [8], [9]. The data sets prepared for staged collisions were fed to the EDSMAC simulation model and the outputs observed were path positions, damage profiles, Collision Deformation Classification (CDC), and delta-V. The measure of accuracy of each of these factors was also presented. Some new features are introduced in EDSMAC4, such as the abilities to include articulated vehicles and add any number of vehicles (the old version of EDSMAC could model only two vehicles). The collision algorithm has also been improved. This EDSMAC4 model has also been validated using staged collisions [10]. The validity of the EDHIS model has been validated by comparing the results of that model with other simulation models and also by staged collisions [11].

1.2 Objectives

The main objective of this thesis is to provide an introduction to crash analysis. This is broken into three sub-objectives. The first sub-objective is to discuss the use of HVE simulation software for accident simulation. The emerging concept of utilizing data recorded in the EDR in order to reconstruct and simulate an accident is the second sub-objective. The EDR data obtained from vehicles involved in the accidents were analyzed and two accidents were simulated. The third sub-objective is to provide the collective study of two HVE simulation methods, EDSMAC4, and EDHIS. Using these two methods, the vehicle and human behaviors during an accident are studied together.

1.3 About This Thesis

In this thesis three accident cases are studied. The cases were available from a company, Wolf Technical Services, based in Indianapolis, Indiana. The company specializes in providing technical and expert opinions about cause analysis of road accidents. The HVE simulation software required for the simulation of accidents was also available at Wolf.

This chapter provided the introduction to the thesis. The second chapter provides a brief introduction of the HVE software and the simulation methods available in that software. The third chapter discusses a simulation of the bus and car accident. This accident is studied to give a brief introduction about the accident reconstruction using conventional methods. The fourth chapter is an overview of the Event Data Recorder (EDR). The chapter explains different types of data recorders and the information being recorded. The fifth and sixth chapters introduce the simulations of other two accidents, three vehicle accident and intersection accident, respectively, using analysis of the EDR data. The data were present for all the vehicles involved in the accidents. The accuracy of the HVE software was tested for the simulated velocity profiles of each vehicle involved in the accident against those obtained from the EDR data. All three accidents were studied using the EDSMAC4 simulation tool. The sixth chapter presents the behavior of the occupant involved in the intersection accident using the EDHIS simulation tool in HVE. The seventh chapter presents conclusions.

2. SIMULATION SOFTWARE: HVE OVERVIEW

HVE is a sophisticated simulation platform which can be used for vehicle design, safety research, and accident simulation. In vehicle design, the dynamic behavior of existing or prototype vehicle can be studied, and vehicle crush stiffness coefficient can be estimated. Advanced features in HVE also provide the simulation of vehicle control systems, brake failures, driver's reactions to a collision, and vehicle occupant behavior. HVE is developed by the company Engineering Dynamics Corporation (EDC).

2.1 HVE Editors

For entering the data associated with an accident, HVE provides five GUI based editors. They are the human editor, the vehicle editor, the environment editor, the event editor, and the playback editor as shown in Figure 2.1. The human, vehicle and environment editors are input editors having databases associated with them. Thus, humans, vehicles and environment similar to those involved in an accident can be chosen from those databases. The event editor is a model where actual simulation is executed. It shows the interactions among objects (humans, vehicles and their environment) selected from the input editors. The event editor allows the various simulation methods to choose such as EDSMAC4, SIMON, and EDHIS. Depending upon specific simulation output requirements the particular simulation model can be chosen. For example, the EDHIS simulation model is used specifically to observe the impact of an accident on a human. The playback editor gives various outputs obtained from simulation such as damage data, accident history, and injury data. The detailed information about each editor and simulation method is presented in the following subsections.

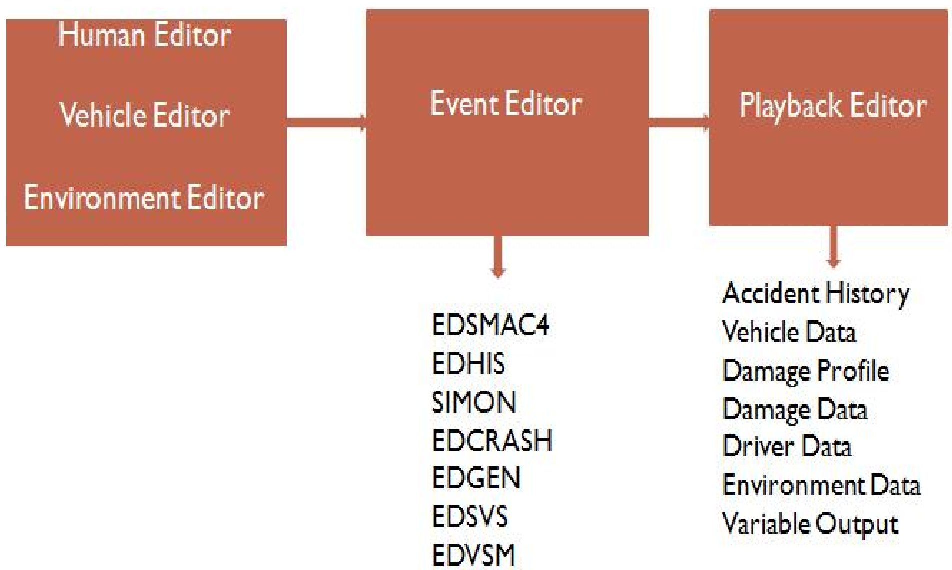


Fig. 2.1. HVE editors

2.1.1 Human Editor

The human editor is used to design pedestrian and vehicle occupant models in 3D. Parameters of a human model include age, sex, weight percentile, and height percentile. HVE-2D does not offer a human editor. Figure 2.2 shows an example of this editor GUI in HVE. In EDHIS a human model consists of three segments: head, torso, and legs and these segments are connected by two ball-shaped joints at the neck and hip [12].

2.1.2 Vehicle Editor

The vehicle editor is used to input vehicle information for simulation purposes. The vehicle is selected from an assortment of vehicle and tire datasets from a standard database EDVDB (Engineering Dynamics Vehicle Data Base). Using this database specific vehicle dynamics, exterior, sprung mass and tires can be created. It provides high fidelity vehicle models and allows the user to select the nearest matching vehicle. It contains vehicle type, make, model, year, and body style. Vehicle types include passenger car, truck, utility vehicle, trailer, and dolly. An extensive review of parameters (weights, stiffness coefficients, tire data etc.) of vehicles is done by EDC engineers before adding those vehicles to the database [12]. Figure 2.3 shows an example of the vehicle editor GUI.

2.1.3 Environment Editor

The purpose of this editor is to input the parameters of the physical environment in which an accident takes place. Several visual environments such as interstate and intersection are already present in the HVE database. Scanned photographs or aerial views of the actual scene taken from Google Earth can also be added in the environment. Such environments must be processed to acquire some physical qualities such as friction [12]. Figure 2.4 shows an example of the environment editor GUI.

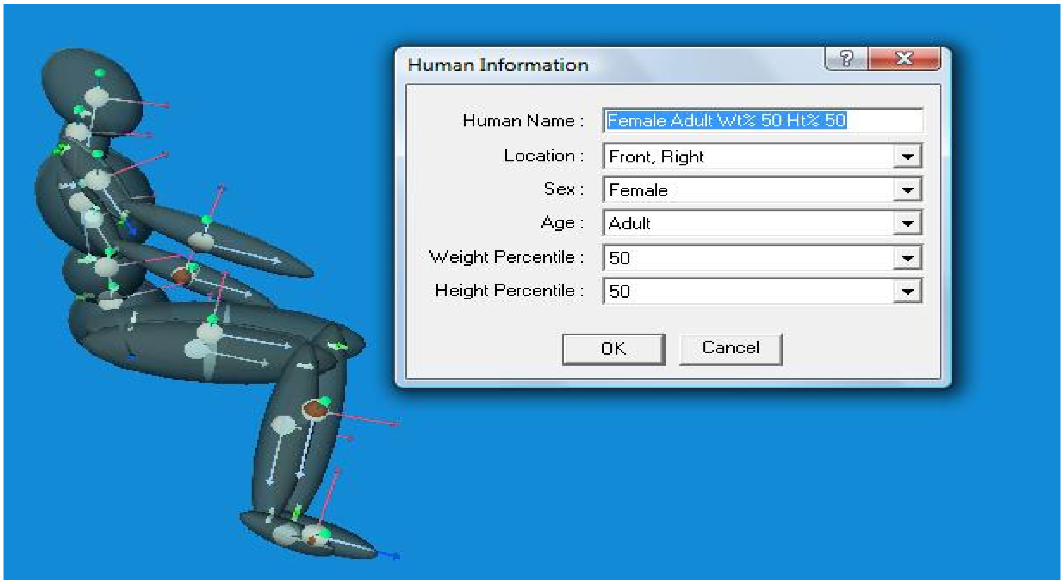


Fig. 2.2. HVE human editor GUI

2.1.4 Event Editor

The inputs to the Event editor are the models of humans, vehicles, and their environments. The event editor is a display tool which shows the interactions among these inputs. Any number of events can be added to the current case. The event controller component present in the editor is used to start, stop, rewind, and fast forward the current event. "Key Results" is a display window which displays a number of outputs associated with the vehicles such as velocity, yaw, pitch, roll, and acceleration, in real time [12]. Figure 2.5 shows an example of the event editor GUI.

2.1.5 Playback Editor

The playback editor is used to examine the outputs obtained during the event simulation. Options include as vehicle damage profiles, accident history, 3-D trajectory simulations, variable output, injury data, and vehicle data. The playback editor is also used to combine two or more events and create a video [12]. Figure 2.6 shows an example of the playback editor GUI.

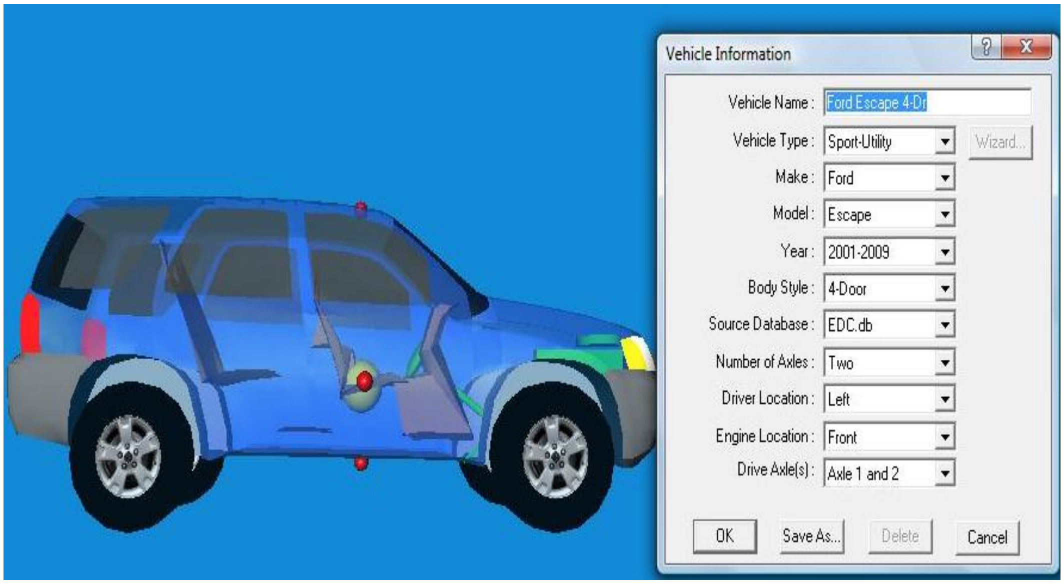


Fig. 2.3. HVE vehicle editor GUI

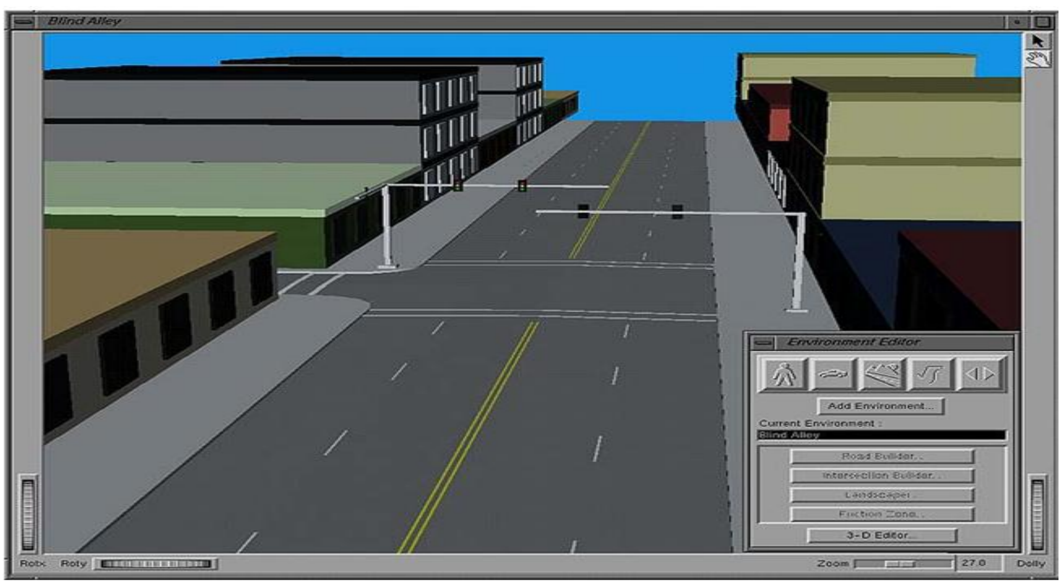


Fig. 2.4. HVE environment editor GUI

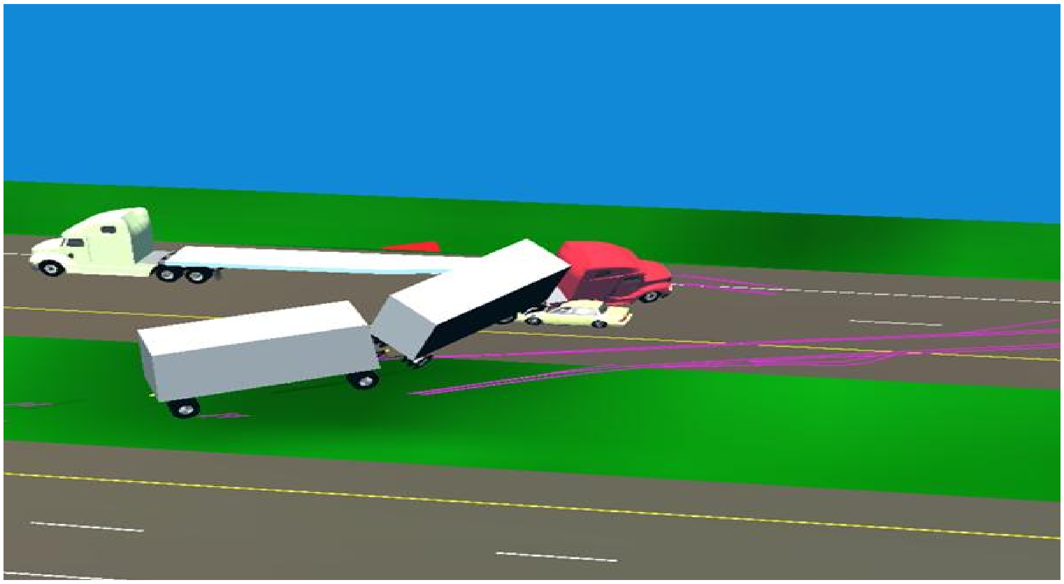


Fig. 2.5. HVE event editor GUI

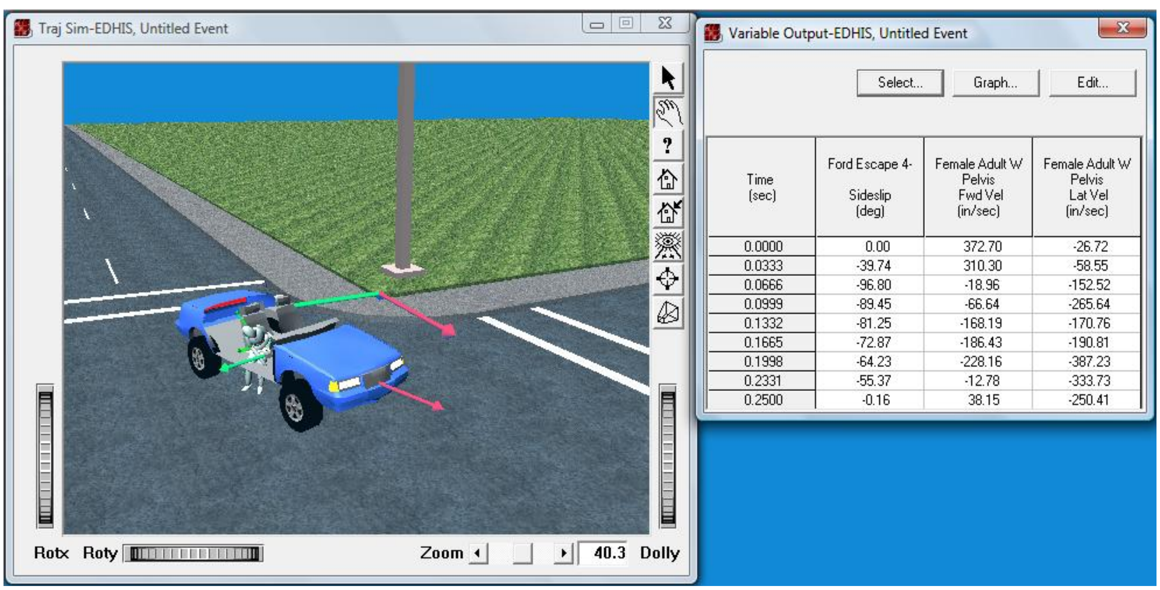


Fig. 2.6. HVE playback editor GUI

2.2 HVE Simulation Methods Used in this Thesis

There are eight simulation models available in HVE, each of which serves a specific purpose [12]. The following two subsections describe three simulation methods which are used in this thesis. The third subsection discusses the other methods available in HVE.

2.2.1 Engineering Dynamics Corporation Simulation Model of Automobile Collisions (EDSMAC4)

This tool is used to simulate and analyze vehicle collisions. It is an extension of the simulation model EDSMAC. It works for any number of vehicles. The vehicle database contains unit vehicles such as passenger cars, pick-up trucks as well as articulated vehicles such as tractors carrying up to three trailers. Different makes, years, and other options such as body style, number of axles, and engine location are available for the specific type of a vehicle. If the specifications of the vehicle involved in the accident are not available in the database the nearest matching specifications can be selected.

For simulation, the EDSMAC4 model uses presumed or calculated inputs such as position and driver controls. Driver controls include braking information and steering angle for each vehicle. Depending on the information entered, the EDSMAC4 produces outputs such as kinematics (position, velocity, and acceleration) and kinetics (tire forces, moments). The program simulates vehicle trajectories and damage profiles. This method can be used to visualize how a crash may have occurred. By varying the initial conditions and driver controls, a user can obtain a simulation that as far as possible matches the known evidence of a real life accident such as tire marks, impact velocity and damage profiles [12].

A limitation of this simulation method is that excessive lateral force results in the termination of an event. Hence it is not an appropriate software for rollover simulations.

2.2.2 Engineering Dynamics Corporation Human Impact Simulator (EDHIS)

The EDHIS method is used to predict and analyze the response of a vehicle occupant or a pedestrian during an impact. The effect of airbag and seatbelt can also be studied using the EDHIS method. A human can be modeled with 12 degrees-of-freedom using this method. The EDHIS method divides the human body in to three masses (head, torso and legs) and two joints (neck and hips) [12].

2.2.3 SImulation MOdel Non-linear (SIMON)

The SIMON provides up to 21 degrees of freedom per vehicle. It contains advanced set of features such as brake designer, ABS control system, and tire-terrain models. SIMON is also used to simulate vehicle roll-overs which cannot be simulated in EDSMAC4.

2.3 Other Available Simulation Methods

Other simulation models available in HVE but not used in this thesis are

Engineering Dynamics Corporation Reconstruction of Accident Speeds on the Highway (EDCRASH) It is used for the analysis of up to two vehicles. EDCRASH is mainly used for estimating the change in velocity based on the information of vehicle deformation [12].

Engineering Dynamics Vehicle Simulation Model (EDVSM) It is used to analyze in 3D, the vehicle's response to a tire blow out event. HVE brake designer system is also supported by EDVSM. The newly introduced closed-loop driver model is included in this simulation tool, in which a user can define the maneuver path and the software defines the steering data required for that maneuver [12].

Engineering Dynamics Vehicle Dynamics Simulator (EDVDS)

The EDVDS is designed to simulate the reaction of commercial vehicles to the inputs such as braking, steering and a 3D road geometry. Depending on these inputs the EDVDS predicts vehicle dynamics such as the tire dynamics and brake system. An articulated vehicle carrying up to three trailers can be simulated in this method.

Engineering Dynamics Corporation GENeral Analysis Tool (EDGEN)

The EDGEN method allows the analysis of one human or one vehicle at a time. This method is used for time versus distance analysis for a human or a vehicle. The inputs needed are the user specified velocities and up to eight locations to estimate the time required to cover the distance between any two locations.

Graphical Articulated Total Body (GATB) The GATB represents a human model with 48 degrees of freedom. Like EDHIS the pedestrian and occupant behavior can be studied using GATB.

2.4 Application of HVE in this Thesis

Based on these capabilities the EDSMAC4 model was selected for the simulations of all three accidents (bus and car accident, three vehicle accident, and intersection accident) discussed in this thesis, because this method is appropriate for vehicle-to-vehicle collisions and it allows the addition of more than two vehicles in an event. In the intersection accident the passenger-side door of the car pops open and the female passenger is thrown out of the car because she is not wearing a seat-belt. The EDHIS simulation method was used for the qualitative analysis of the passenger's response to the impact in the restrained and unrestrained conditions. The GATB simulation method could not be used because it was not available.

3. BUS AND CAR ACCIDENT

In this chapter a collision of a bus to the rear of a car is studied. The estimation of impact velocity and initial velocities of the vehicles is based on the conservation of energy and conservation of linear momentum, respectively. A scaled AutoCAD diagram was available representing the road geometry and tire-marks obtained by the car. Using this diagram and the EDSMAC4 method in HVE a simulation of the accident is performed to verify the estimated impact velocity, the tire-marks and the rest position of the car as indicated in the AutoCAD drawing.

3.1 Accident Scenario

A 1998 Greyhound bus hit the rear of a 2005 Subaru Impreza in the right lane of a four-lane highway. The bus, occupied by six passengers, was traveling northbound. The road consisted of total four lanes, two lanes southbound and two lanes northbound. The Subaru, traveling in the same direction and in the same right lane, was in front of the bus. After being struck, the Subaru rotated because of the impact and moved forward. It ended up in the southbound passing lane. The bus traveled 635 ft. after impact and came to a controlled stop on the shoulder of the northbound lane [13]. The aims of the simulation of this accident were to compare the impact velocity obtained by the simulation to that estimated from the calculations, generate damage profiles of the vehicles, and confirm by simulation that the tire-marks observed at the accident site are consistent with those that could have been generated by the Subaru.

3.2 Preliminary Calculations Using Conservation of Energy and Momentum

This accident reconstruction was done by Mr. Kevin Johnson from Wolf Technical Services. This section explains the calculations performed by Mr. Johnson to find pre-impact and post-impact velocities associated with the vehicles. The conservation of energy was used to calculate the velocity of the Subaru at impact. The conservation of energy requires that the kinetic energy at time t_2 should equal the difference between the kinetic energy at time t_1 and the integral of the force applied over the distance the vehicle moves over time interval. So for each vehicle,

$$\frac{1}{2}mv_1^2 = \frac{1}{2}mv_2^2 + mfgd, \tag{3.1}$$

where the term on the left hand side is the kinetic energy of the vehicle of mass m moving at velocity v_1 at the time t_1 of impact, the first term on the right hand side is the kinetic energy when the vehicle comes to rest at time t_2, and the second term on the right is the integral of the drag force mgf applied by the brakes or the road to the vehicle when the brakes are applied or the vehicle skids. Here constant deceleration over the distance is assumed. As long as the mass of the vehicle does not change due to the impact we can apply (3.1) to determine the velocity at impact if we have a good estimate of the drag factor and the distance traveled after impact. The stopped vehicle has v_2=0. So the impact velocity is,

$$v_i = v_1 = \sqrt{2fgd}. \tag{3.2}$$

Using (3.2) the impact velocity estimated to be 64 mph [13]. The initial velocity range estimated for the Subaru was 17-32 mph.

The pre-impact velocity of the bus was estimated using conservation of momentum. Momentum is a measure of motion of an object with mass m and velocity v. The momentum of the object remains constant until acted upon by the external force. As the momentum is a conservative quantity, when two objects act upon each other the total momentum before the action (in this case impact) equals the total momentum after the action (impact). That means for the bus-car impact, that

$$w_b v_b + w_c v_c = (w_b + w_c) v_i, \tag{3.3}$$

where the left side represents total momentum before impact and the right side represents the total momentum after impact, the first term on the left side represents the pre-impact momentum of the bus with velocity v_b and weight w_b, the second term on the left side indicates the pre-impact momentum of the Subaru having velocity v_c and weight w_c, v_i indicates the impact velocity. As the vehicles travel with the same velocity after impact as long as they are in contact with each other, the velocity immediately after impact is same for both the vehicles. The mass m is weight divided by the gravitational force g. As g is a common term it is canceled and (3.3) is obtained.

The weight of the bus at impact was 27,500 pounds and that of the Subaru at impact was 2963 pounds. From the energy loss calculations the estimated impact velocity was 64 mph and the pre-impact velocity of the Subaru was 17 mph. Hence, using (3.3) the pre-impact velocity of the bus was estimated which was approximately 70 mph. Using these velocity estimates and AutoCAD drawing the simulation was performed. The following section illustrates the steps taken to simulate the accident in HVE.

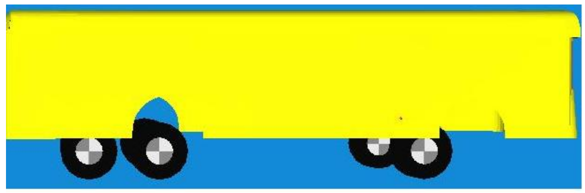
3.3 Setting Up the Simulation

This section illustrates the input parameters selected for the accident simulation. The first subsection gives information about the vehicles chosen from the HVE vehicle editor, the second subsection discusses the environments used from the HVE environment editor and the third subsection demonstrates the actual simulation steps.

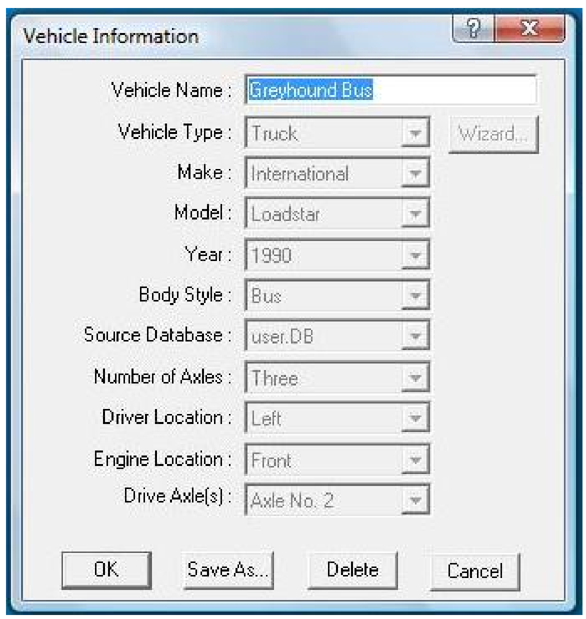
3.3.1 Description and Construction of Vehicle Models

Virtual models of the Greyhound bus and the Subaru were created using the vehicle editor in HVE.

The Greyhound Bus The bus was a 1998 Motor Coach Industries model MC-12. The type "Bus" was not available in HVE. So the nearest possible vehicle type, "Truck," was selected. The make selected was "International". The outer geometricprofile selected was "School Bus"to make the vehicle look like the bus. Figures 3.1(a) and 3.1(b) show the outer profile and the specifications chosen for the bus from HVE vehicle editor.



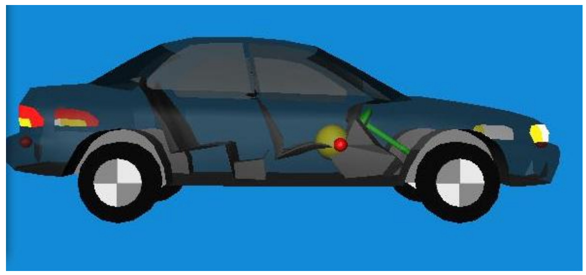
(a) The geometric profile of the Greyhound bus



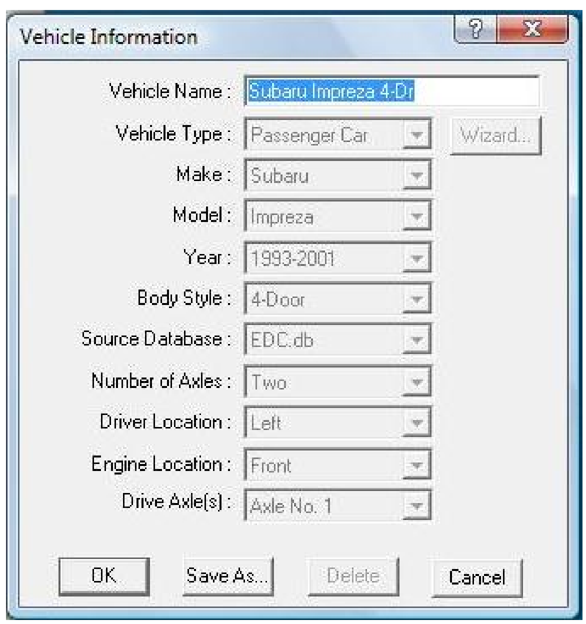
(b) The characteristics chosen to create the bus

Fig. 3.1. Geometry and characteristics of the Greyhound bus

The Subaru The car involved in the accident was a 2005 Subaru Impreza. The make selected was "Subaru". The type selected was "Impreza". The year of the car selected was "1993-2001". Figures 3.2(a) and 3.2(b) show the outer profile and the specifications chosen for the Subaru from HVE vehicle editor.



(a) The geometric profile of the Subaru: The circle near the center of the vehicle indicates the center of gravity



(b) The characteristics chosen to create the Subaru

Fig. 3.2. Geometry and characteristics of the Subaru

3.3.2 Environment

Two environments were used for the simulation. The first environment, "4-LaneFreeway," was available in the HVE environment database. The second environment, created using AutoCAD was available at Wolf. This environment reflected the accurate road geometry, tire-marks and the impact and final positions of the vehicles [13]. The following sections give a brief introduction to these environments.

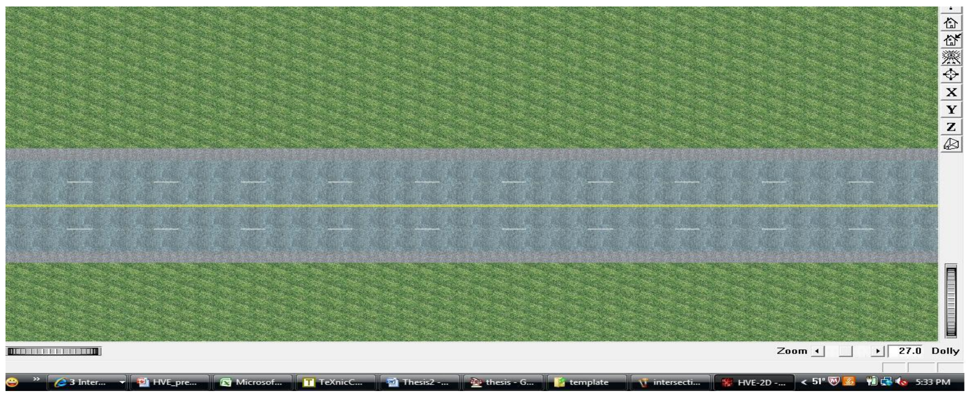
4-LaneFreeway The 4-LaneFreeway.h3d environment was selected, because it matched the road description. It is shown in Figure 3.3(a).

AutoCAD Environment The AutoCAD environment gave the virtual visualization of pre-established tire marks of the car after impact, the starting positions of the bus and the car, the position of the impact and the rest position of both vehicles.

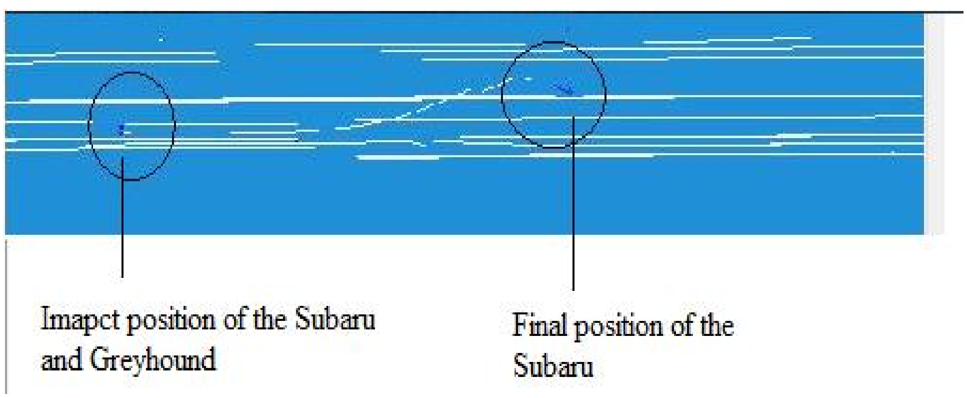
The data from the site survey and photographs of the crash site were imported into AutoCAD in order to increase the accuracy and ease of the simulation. This environment is shown in Figure 3.3(b).

3.3.3 Simulation

The accident was simulated using EDSMAC4, one of the simulation methods in HVE. The five parts of Figure 3.4, on pages 22 and 23, show the sequential events in the collision. At first the initial velocities of the bus and the car were entered. Then the vehicles were moved to their respective locations as shown in Figure 3.4(a).

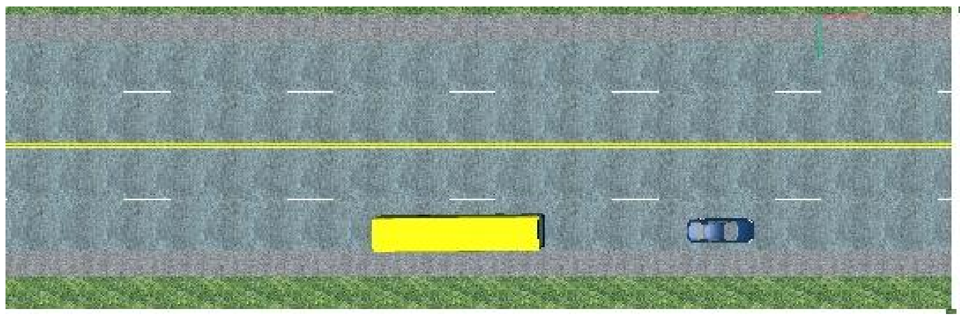


(a) Built-in environment

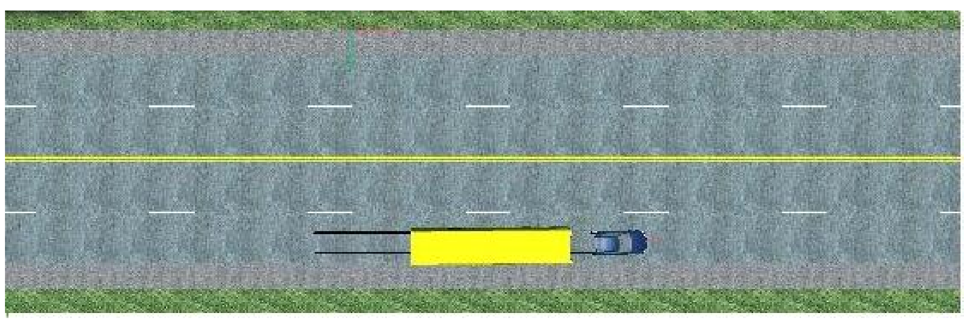


(b) AutoCAD environment

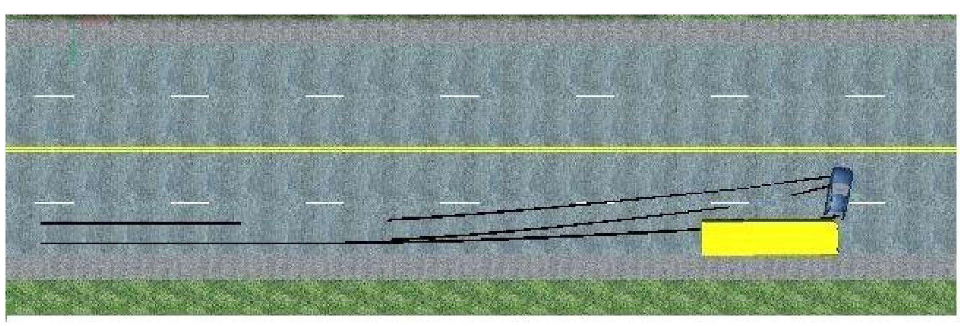
Fig. 3.3. Environments



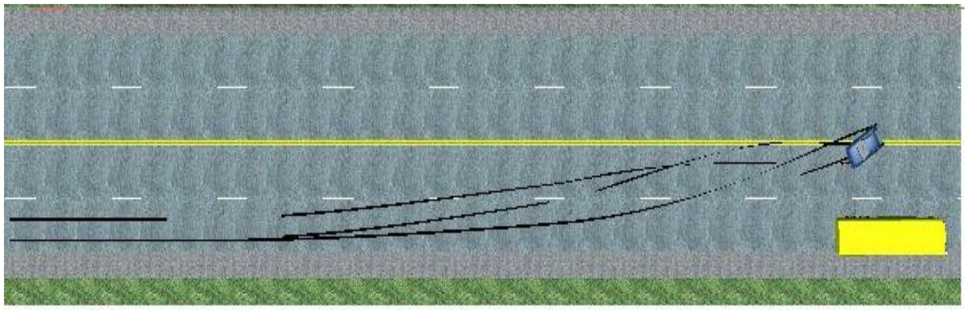
(a) The initial positions of the bus and the car



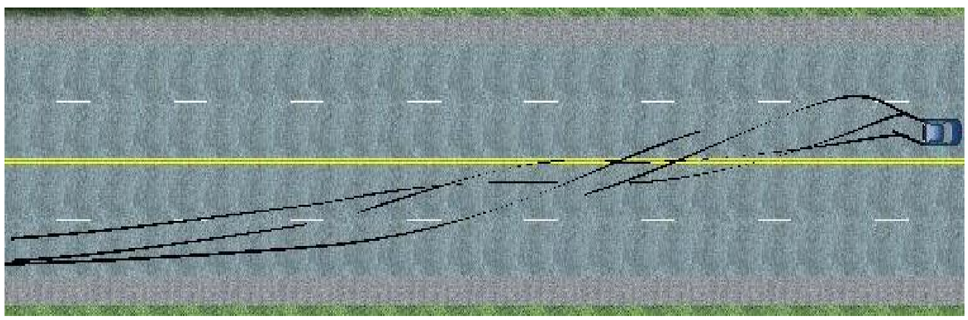
(b) The bus and the car after impact



(c) The car loses control and starts rotating due to impact



(d) The rotation continues



(e) The final positions of the Subaru

Fig. 3.4. Sequential simulation for bus-car accident

The initial velocity of the bus, entered in the simulation, was 70 mph and that of the Subaru was 17 mph. The pre-collision braking, steering or acceleration parameters were not added. The post-collision full braking and partial braking were entered for the Subaru and the bus, respectively. Figure 3.4(b) shows the positions of the vehicles immediately after impact. Figures 3.4(c) and 3.4(d) show the path traveled by the car after impact. Figure 3.4(e) shows the rest position of the car.

Figure 3.5 represents the accident simulation using the AutoCAD surface, which indicates the pre-established tire marks and the scaled stopping distance of the car and the bus. A number of iterations of the simulation were performed in order to

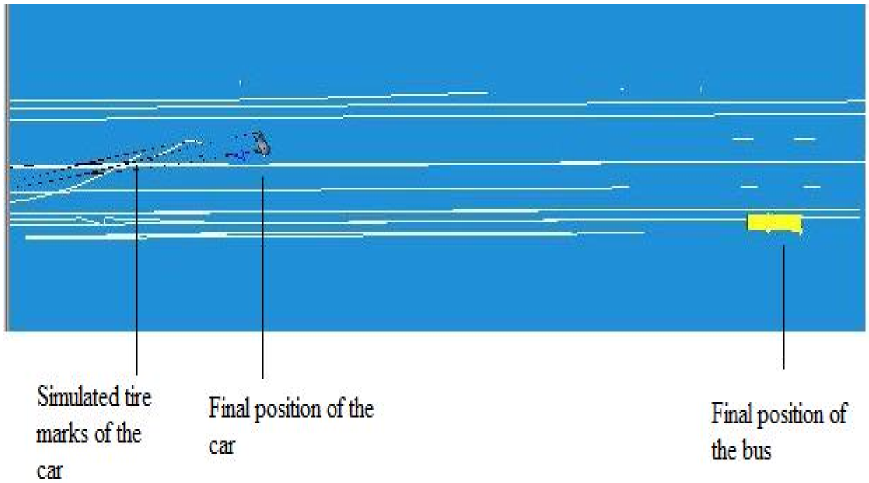


Fig. 3.5. Bus-Car collision execution on AutoCAD surface

match the tire marks obtained in the simulation with the pre-established tire marks on the AutoCAD surface.

3.4 Results of the Simulation

This section discusses the outputs obtained from the simulation based on the input parameters entered above. The first subsection presents the position-error calculation for the rest position of the Subaru and the second subsection shows the velocity graph for both the vehicles and the third subsection gives the qualitative analysis of the damage profiles of the vehicles.

3.4.1 Position Error Calculation

The position error is computed based on the actual position of a vehicle on the road at the time of an accident and its predicted position. The actual rest position of the Subaru was marked on the AutoCAD surface. So it was possible to get the co-ordinates of that position [14]. The position error was calculated using,

$$Error = \frac{(\Delta X, Y)}{L_{act}} * 100, \tag{3.4}$$

where $\Delta X, Y$ is the difference between actual rest position and simulated rest position, and L_{act} is the actual length of the path traveled by vehicle after impact which was directly available from the accident-reconstruction report [13]. $\Delta X, Y$ is calculated by,

$$\Delta X, Y = \sqrt{(X_{sim} - X_{act})^2 + (Y_{sim} - Y_{act})^2}, \tag{3.5}$$

where (X_{sim}, Y_{sim}) is the rest position obtained in simulation and (X_{act}, Y_{act}) is the actual rest position and L_{act} was approximately 280 ft [13]. Using the actual and simulated co-ordinates in Table 3.1 and the L_{act}, the position error obtained was 7.8%.

Table 3.1
The actual and simulated co-ordinates of the rest position of the Subaru

	Actual	Simulated
X	34.4	30
Y	310.1	289.8

3.4.2 Velocity Graph

Graph shown in Fig. 3.6 indicates the range of velocities, approximately 62 mph to 65 mph. at the impact which is in good agreement with the estimated impact velocity 64 mph.

3.4.3 Damage Profiles of The Vehicles

Figures 3.7(a) and 3.7(b), on page 27, show the qualitative comparison of real-life and simulated damage profiles of both the vehicles. Because of the difficulty of quantifying profile damage, no attempt was made to present a quantitative comparison.

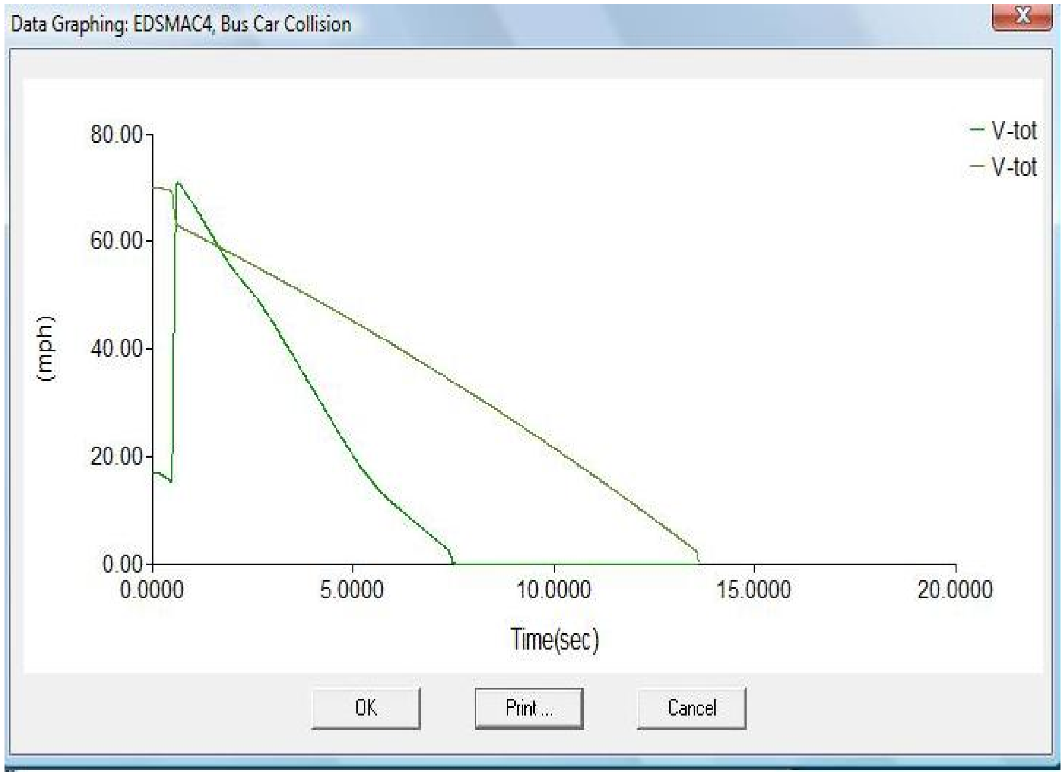
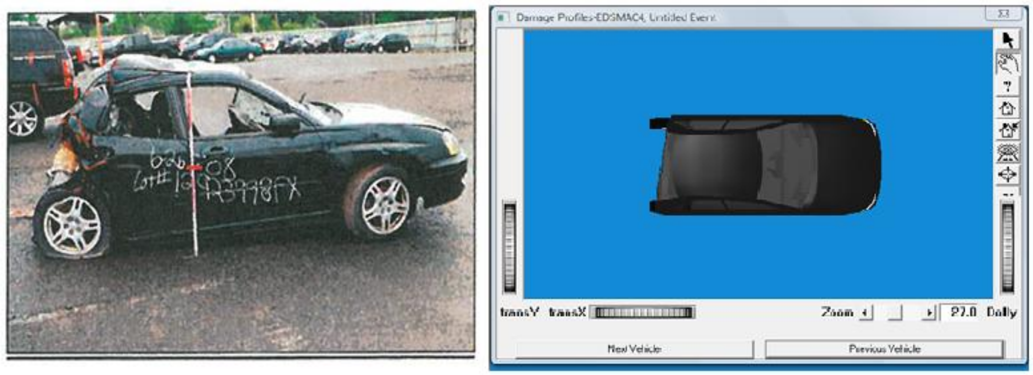


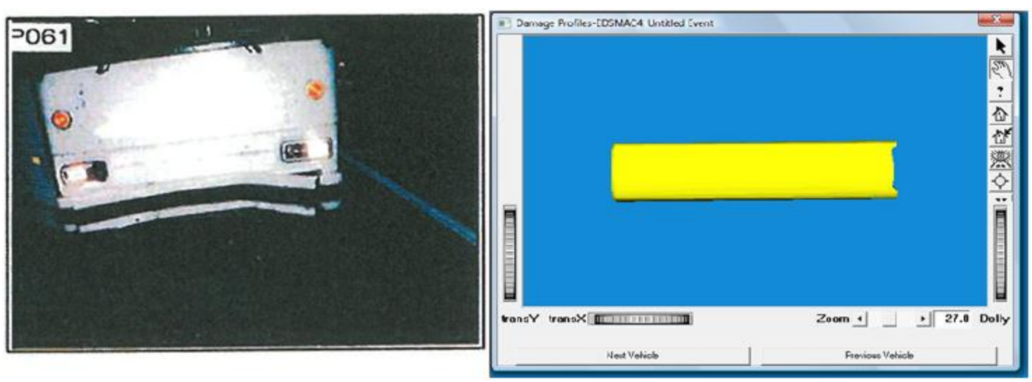
Fig. 3.6. Graph of velocity profiles for the bus and the car

3.5 Summary and Conclusion

For this accident, the EDSMAC4 simulation method in HVE was used to estimate the position error and impact velocity, to obtain skid-marks for the Subaru and to qualitatively analyze the damage profiles of the vehicles. The rest position of the Subaru and the impact velocity were verified in the simulation. For given input parameters such as initial velocities and scaled, road geometry, the output parameters; impact velocity, damage profiles and tire-marks obtained from simulation are matching with the real-life evidence. Thus, it can be concluded that the simulation provides strong support to the accident reconstruction performed using conservation of energy and linear momentum.



(a) Subaru real life and simulated damage profile



(b) Greyhound bus real life and simulated damage profile damage profile

Fig. 3.7. Damage profiles

4. EDR: EVENT DATA RECORDER

The accident analyses in chapters 5 and 6 use EDR data. Hence this chapter provides a brief introduction to the EDR. The EDR is usually a subcomponent within the ECM (Electronic Control Module) used in heavy duty trucks and the PCM (Power-train Control Module) used in passenger vehicles. The EDR has the ability to capture parameters such as vehicle speed, acceleration, air-bag deployment, and seat-belt status. The EDR requires battery power for at least 2 seconds after an accident to record a complete cycle. The data stored in the EDR are in Hexadecimal format. The EDR runs an algorithm that monitors sensor data and deploys the airbag and other restraint systems if the certain parameter has reached its threshold value.

4.1 Background

The EDRs are developed and installed by the OEMs (Original Equipment Manufacturers) or aftermarket suppliers. The EDRs supplied by the aftermarket systems include tachographs, electronic recorders, accident data recorders, and video recorders. These EDRs are mainly used in fleet applications. The EDRs supplied by the OEMs are used in commercial as well as passenger vehicles. The EDRs have different names depending on the manufacturer [1].

4.2 Commercial Vehicles EDRs

The EDRs of heavy duty trucks are usually known as ECMs (Electronic Control Modules). They control the operation of an engine and improve the engine performance. The ECMs continuously record the information about vehicles and respective engines. The information in the ECMs contains the collision dynamics such as velocity, acceleration, and a driver's maneuver before and after collision. Data available from the ECMs are described below.

Monthly Activity These pages contain the activity over the previous three months. The same parameters as those of Trip Activity are recorded. If the truck is inactive for a few months, the three months data would be for the last three months that it was driven. An example of this data page is shown in Figure A.1 of Appendix.

Trip Activity This indicates the behavior of a driver and a vehicle during trips. The main parameters contain trip distance, trip fuel, fuel economy, driving time, and driving economy. A typical page of Trip Activity is shown in Figure A.2 of Appendix.

Diagnostic Records These records contain the three most recent active fault codes for oil pressure, oil level, and temperature. If any of these three parameters goes out of range, the active fault code will be generated. A total of twelve data points are captured within a five-second interval. These data points contain the vehicle speed, engine speed, oil, and fuel temperatures and pressures. These records indicate whether the engine brake, service brake, accelerator, clutch or/and cruise control were active at that time. A typical Diagnostics page is shown in Figure A.3 of Appendix.

Daily Engine Usage These pages record the engine-usage data of the most recent 30 days during which the engine was active. The pages record the engine start time, odometer, the total distance traveled , fuel consumption, fuel economy and average speed. A typical Daily Engine Usage page is shown in Figure A.4 Appendix.

Last Stop Record From standpoint of crash reconstruction, these are the most important and useful pages because they record the parameters during the vehicle's last stop. If these pages are properly preserved, they directly give the readings at the time of collision. The data spanning the minute and 45 seconds prior to the vehicle coming to the stop and fifteen seconds after the stop will be recorded. This data will contain engine speed, vehicle speed, brake, clutch actuation, engine load, throttle position plus cruise control (if it was in use), and any active diagnostic codes. A typical Last Stop Record page is shown in Figure 4.1 on page 31.

Hard Brake # 1 and # 2 The ECM contains two hard brake reports. These are similar to the last stop record, but for a shorter period of time. The Hard Brake pages record 1 minute of data before impact and 15 seconds after impact. Hard Brake # 1 contains the information of a first-recent event and Hard Brake # 2 contains the information of a second-recent event. A typical Hard Brake # 1 page is shown in Figure 4.2 on page 32.

4.3 Passenger Vehicles EDRs

Some automobile manufactures record data with the help of the airbag sensors, anti-lock brake system, and power-train control modules. These data are stored in the EDRs. Different manufacturers have given different names to the EDRs. For example, the GM's EDRs are known as SDMs (Sensing and Diagnostic Modules) and Ford's EDRs are known as RCMs (Restraint Control Modules). The examples of the data which can be recorded in RCMs are shown in some of the following figures. Figure 4.3 shows the pre-crash data, including parameters such as vehicle speed, ABS activity, and engine rpm. Figure 4.4 also shows the pre-crash data which includes parameters such as seat-belt status and occupant size classification. Figure 4.5 shows the longitudinal crash pulse data.

DDEC® Reports - Last Stop Record

Print Date: Nov 02, 2004 12:41 PM (CST)

Truck City of Gary
7360 W. Chicago Ave.
Gary, In 46406
1-800-552-4420

Trip: 02/28/2004 to 11/02/2004 (EST)
Vehicle ID: 13955
Driver ID:
Odometer: 615907.1 mi

Last Stop Time: 10/30/2004 10:49:03 (EST)

Last Stop Odometer: 615907.1 mi

Time	Vehicle Speed (mph)	Engine Speed (rpm)	Brake	Clutch	Engine Load (%)	Throttle (%)	Cruise	Diagnostic Code
-0:19	18.0	597	No	No	22.50	0.00	No	Yes
-0:18	18.0	602	No	No	19.00	0.00	No	Yes
-0:17	18.5	598	No	No	22.50	0.00	No	Yes
-0:16	18.0	602	No	No	19.00	0.00	No	Yes
-0:15	18.5	600	No	No	21.00	0.00	No	Yes
-0:14	18.0	601	No	No	20.00	0.00	No	Yes
-0:13	18.0	600	No	No	20.50	0.00	No	Yes
-0:12	18.0	603	No	No	19.00	0.00	No	Yes
-0:11	18.0	601	No	No	20.00	0.00	No	Yes
-0:10	17.5	601	No	No	24.00	0.00	No	Yes
-0:09	18.0	595	No	No	27.00	0.00	No	Yes
-0:08	17.5	601	No	No	22.50	0.00	No	Yes
-0:07	18.0	598	No	No	25.50	0.00	No	Yes
-0:06	17.5	600	No	No	24.00	0.00	No	Yes
-0:05	18.0	598	No	No	26.00	0.00	No	Yes
-0:04	17.5	600	No	No	23.00	0.00	No	Yes
-0:03	18.0	599	No	No	24.50	0.00	No	Yes
-0:02	18.0	599	No	No	24.00	0.00	No	Yes
-0:01	18.0	600	No	No	25.00	0.00	No	Yes
0:00	9.5	318	No	No	0.00	0.00	No	Yes
+0:01	0.0	0	No	No	0.00	0.00	No	Yes
+0:02	0.0	0	No	No	0.00	0.00	No	Yes
+0:03	0.0	0	No	No	0.00	0.00	No	Yes
+0:04	0.0	0	No	No	0.00	0.00	No	Yes
+0:05	0.0	0	No	No	0.00	0.00	No	Yes
+0:06	0.0	0	No	No	0.00	0.00	No	Yes
+0:07	0.0	0	No	No	0.00	0.00	No	Yes
+0:08	0.0	0	No	No	0.00	0.00	No	Yes
+0:09	0.0	0	No	No	0.00	0.00	No	Yes
+0:10	0.0	0	No	No	0.00	0.00	No	Yes
+0:11	0.0	0	No	No	0.00	0.00	No	Yes
+0:12	0.0	0	No	No	0.00	0.00	No	Yes
+0:13	0.0	0	No	No	0.00	0.00	No	Yes
+0:14	0.0	0	No	No	0.00	0.00	No	Yes
+0:15	0.0	0	No	No	0.00	0.00	No	Yes

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11024SAE.XTR Engine S/N: 06R0633524 ECM S/W Version: 29.04 Version 6.00 Page 3

Fig. 4.1. Last-stop record

4.4 Application of EDR Data in this Thesis

The EDR-types of the vehicles involved in the accidents discussed in Chapters 5 and 6 were the RCM, the ECM, and the SDM. In Chapter 5, the collision of two semis and one car is discussed. The ECM data from the semis and the SDM data from the car were available. In chapter 6, the collision of the cars at the intersection is studied. The RCM data were available from both the cars.

DDEC® Reports - Hard Brake #1

Print Date: Nov 02, 2004 12:41 PM (CST)

Truck City of Gary
7360 W. Chicago Ave.
Gary, In 46406
1-800-552-4420

Trip: 02/28/2004 to 11/02/2004 (EST)
Vehicle ID: 13955
Driver ID:
Odometer: 615907.1 mi

Trip Distance	126246.3 mi	Trip Time	2717:05:09
Trip Fuel	18090.50 gal	Fuel Consumption	6.66 gal/h
Fuel Economy	6.98 mpg	Idle Time	405:45:16
Avg Drive Load	49 %	Idle Percent	14.93 %
Avg Vehicle Speed	54.6 mph	Idle Fuel	142.00 gal

Incident Time: 10/30/2004 10:48:15 (EST)   Incident Odometer: 615906.8 mi

Time	Vehicle Speed (mph)	Engine Speed (rpm)	Brake	Clutch	Engine Load (%)	Throttle (%)	Cruise	Diagnostic Code
-1:00	62.0	1552	No	No	76.00	0.00	Yes	No
-0:59	62.0	1553	No	No	78.00	0.00	Yes	No
-0:58	62.0	1548	No	No	82.00	0.00	Yes	No
-0:57	62.0	1537	No	No	90.50	0.00	Yes	No
-0:56	62.0	1547	No	No	87.00	0.00	Yes	No
-0:55	62.0	1556	No	No	78.00	0.00	Yes	No
-0:54	62.0	1555	No	No	74.00	0.00	Yes	No
-0:53	62.0	1556	No	No	67.50	0.00	Yes	No
-0:52	62.0	1560	No	No	70.00	0.00	Yes	No
-0:51	62.0	1546	No	No	82.00	0.00	Yes	No
-0:50	62.0	1553	No	No	79.50	0.00	Yes	No
-0:49	62.0	1549	No	No	77.50	0.00	Yes	No
-0:48	62.0	1556	No	No	73.00	0.00	Yes	No
-0:47	62.0	1550	No	No	72.50	0.00	Yes	No
-0:46	62.0	1544	No	No	75.50	0.00	Yes	No
-0:45	62.0	1535	No	No	82.50	0.00	Yes	No
-0:44	62.0	1549	No	No	77.00	0.00	Yes	No
-0:43	62.0	1549	No	No	82.00	0.00	Yes	No
-0:42	62.0	1540	No	No	90.00	0.00	Yes	No
-0:41	62.0	1545	No	No	97.00	0.00	Yes	No
-0:40	62.0	1543	No	No	99.50	0.00	Yes	No
-0:39	62.0	1544	No	No	99.50	0.00	Yes	No
-0:38	61.5	1541	No	No	100.00	0.00	Yes	No
-0:37	62.0	1539	No	No	100.00	0.00	Yes	No
-0:36	62.0	1546	No	No	97.50	0.00	Yes	No
-0:35	62.0	1547	No	No	97.50	0.00	Yes	No
-0:34	62.0	1545	No	No	100.00	0.00	Yes	No
-0:33	61.5	1542	No	No	100.00	0.00	Yes	No
-0:32	61.5	1538	No	No	100.00	0.00	Yes	No
-0:31	61.5	1537	No	No	100.00	0.00	Yes	No
-0:30	61.5	1530	No	No	100.00	0.00	Yes	No
-0:29	61.5	1527	No	No	100.00	0.00	Yes	No
-0:28	61.0	1516	No	No	100.00	0.00	Yes	No
-0:27	60.5	1523	No	No	100.00	0.00	Yes	No
-0:26	60.5	1514	No	No	100.00	0.00	Yes	No
-0:25	60.5	1501	No	No	100.00	0.00	Yes	No
-0:24	60.5	1512	No	No	100.00	0.00	Yes	No
-0:23	60.5	1515	No	No	100.00	0.00	Yes	No
-0:22	60.5	1514	No	No	100.00	0.00	Yes	No
-0:21	60.5	1514	No	No	100.00	0.00	Yes	No

11024SAE.XTR Engine S/N: 06R0633524 ECM S/W Version: 29.04 Version 6.00 Page 1

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Fig. 4.2. Hard-brake record

Pre-Crash Data -5 to 0 sec [2 samples/sec] (First Record)

Times (sec)	Speed vehicle indicated MPH [km/h]	Accelerator pedal, % full	Service brake, on/off	Engine rpm	ABS activity (engaged, non-engaged)	Stability control (engaged, non-engaged)	Traction Control via Brakes (engaged, non-engaged)	Traction Control via Engine (engaged, non-engaged)
- 5.0	21.7 [35.0]	0	ON	1,200	non-engaged	non-engaged	non-engaged	non-engaged
- 4.5	20.5 [33.0]	0	ON	1,000	non-engaged	non-engaged	non-engaged	non-engaged
- 4.0	18.6 [30.0]	0	ON	900	non-engaged	non-engaged	non-engaged	non-engaged
- 3.5	18.0 [29.0]	0	ON	900	non-engaged	non-engaged	non-engaged	non-engaged
- 3.0	16.8 [27.0]	0	ON	800	non-engaged	non-engaged	non-engaged	non-engaged
- 2.5	15.5 [25.0]	0	ON	800	non-engaged	non-engaged	non-engaged	non-engaged
- 2.0	14.9 [24.0]	0	ON	800	non-engaged	non-engaged	non-engaged	non-engaged
- 1.5	14.9 [24.0]	0	ON	1,100	non-engaged	non-engaged	non-engaged	non-engaged
- 1.0	14.9 [24.0]	0	OFF	1,200	non-engaged	non-engaged	non-engaged	non-engaged
- 0.5	11.8 [19.0]	3	ON	1,000	non-engaged	non-engaged	non-engaged	non-engaged
0.0	11.8 [19.0]	100	OFF	2,100	non-engaged	non-engaged	non-engaged	non-engaged

Fig. 4.3. RCM pre-crash data

Pre-Crash Data -1 sec (First Record)

Ignition cycle, crash	3,760
Frontal air bag warning lamp, on/off	OFF
Occupant size classification, front passenger (Child size Yes/No [Hex value])	No [$08]
Frontal air bag suppression switch status, front passenger	N/A
Safety belt status, driver	Driver Not Buckled
Seat track position switch, foremost, status, driver	Not Forward
Safety belt status, front passenger	Passenger Not Buckled
Brake Telltale	Off
ABS Telltale	Off
Stability Control Telltale	Off
Speed Control Telltale	Off
Powertrain Wrench Telltale	Off
Powertrain Malfunction Indicator Lamp (MIL)Telltale	Off
HEV Hazard Telltale	Off

Fig. 4.4. RCM pre-crash data

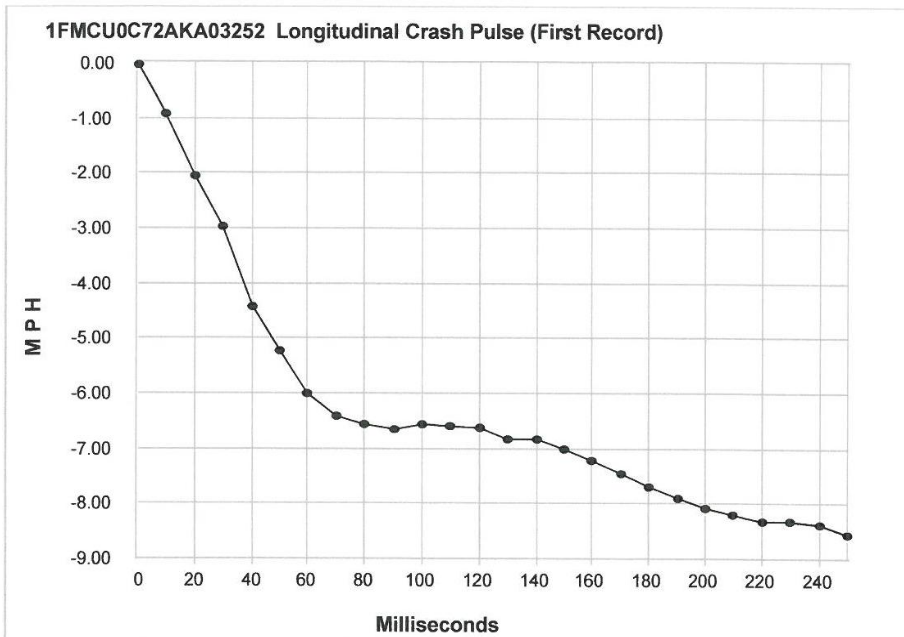


Fig. 4.5. RCM longitudinal crash pulse

5. THREE VEHICLE COLLISION

This chapter discusses an accident simulation using EDR data for a collision of two trucks and one car on an interstate. All vehicles involved in this accident had EDR data. As discussed in the previous chapter, the EDR data provides information about various parameters for a period of time before and after impact. According to the Indiana state police report, the information obtained from the EDR data of the vehicles involved in this accident was consistent with the real-life evidence [15]. Therefore, these data are used for the accident simulation. A 3D AutoCAD drawing reflecting the road geometry and pre-established tire-marks was also available. The purpose of the simulation was to confirm that, the tire-marks observed on the road were generated by one of the trucks and present the comparison of the velocity profiles obtained the HVE simulation and the EDR data.

5.1 Accident Scenario

A yellow 2001 Volvo semi cab pulling two trailers was traveling on the westbound side of I-80/90 at 62 mph. A yellow 2004 Freightliner cab pulling one trailer and a Buick Century automobile were traveling on I-80/90 eastbound. The initial speeds of the Freightliner and the Buick were 59 and 70 mph respectively.

The driver of the Volvo lost control. His vehicle crossed the passing lane, went over a grass median for 103 feet, then entered the eastbound driving lane. The Volvo hit the Freightliner at its fourth axle. The impact speed was 43 mph. Due to this impact, the first trailer of the Volvo began rolling toward its right side. At the same time, the Buick drove into and under the same trailer. Finally, the first trailer of the Volvo came to rest directly on top of the Buick. The speed of the Buick at the time of impact was 23 mph. The EDR data were preserved and available for all three vehicles [15].

5.2 Preliminary Calculations Using the EDR Data from All the Vehicles

The two trucks involved in the accident had ECMs and the Buick had an SDM. The hard-brake record data in the ECMs and pre-crash data in the SDM were used for the simulation. The sections below describe this EDR information for each vehicle and its use in the simulation.

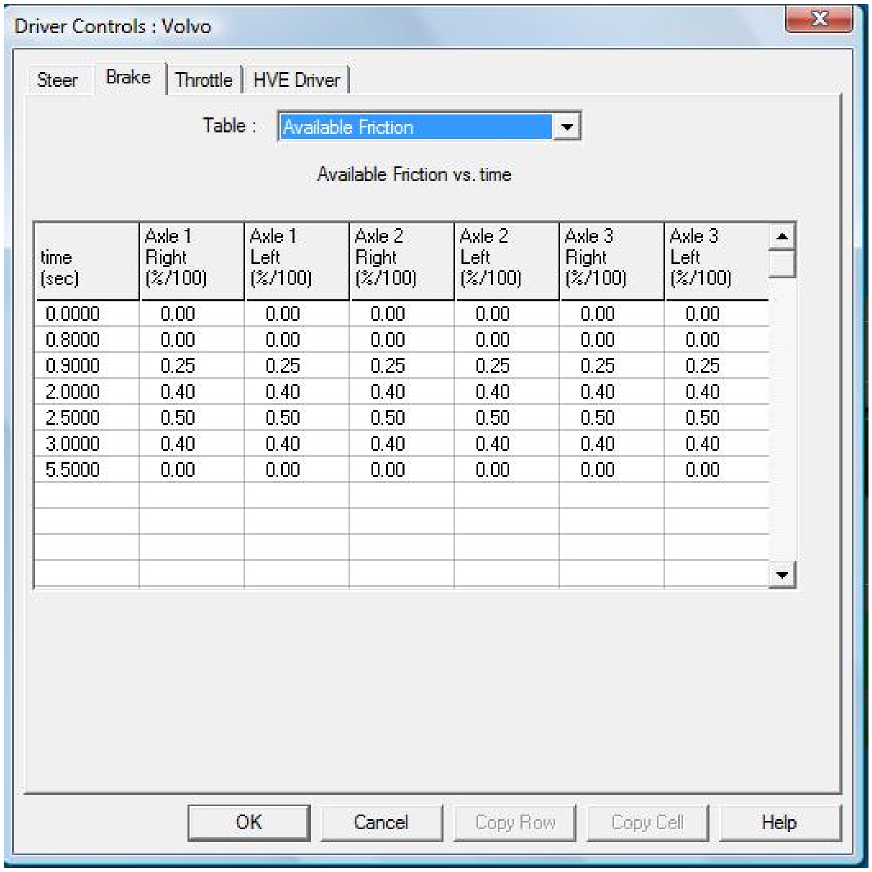
5.2.1 Volvo EDR-data and Its Use in Simulation

The EDR data, from the ECM had data pages such as Last Stop Activity, Hard Brake and Diagnostics Records. The variable used for the simulation was "Hard Brake # 1." These data provided information about the speed of the vehicle one minute prior to through 15 seconds after impact. Table 5.1 shows the data for ten seconds before impact. As shown in the table , ten seconds before impact the velocity of the Volvo was 62.5 mph. The time of impact was 0 seconds. The speed of the Volvo at the time of impact was 43.5 mph. Ten seconds prior to the accident the cruise control was on. The brakes were applied seven seconds before the impact. Four seconds after that the engine speed slowed down and the brakes were released. The brakes were applied again for seconds −2, −1 and 0.

According to the police report, four seconds before the accident, the Volvo started going out of the lane and entered into the grass median. The initial speed was 60.5 mph. The HVE event-editor provides an input friction table which indicates the available friction at particular time. The friction values have to be entered in that table to achieve specific velocity at particular time. The reference value for this friction was calculated using deceleration observed four seconds before impact. The acceleration or deceleration force in the direction of motion divided by the object's

Table 5.1
EDR hard brake information for the Volvo

Time	Vehicle Speed (mph)	Engine Speed (rpm)	Brake	Cruise
−10	62.5	1554	No	Yes
−9	62.5	1555	No	Yes
−8	62.0	1554	No	Yes
−7	62.0	1550	Yes	No
−6	61.5	1535	No	No
−5	61.0	1523	No	No
−4	60.5	1506	No	No
−3	59.5	1488	No	No
−2	57.5	1437	Yes	No
−1	53.0	1307	Yes	No
0	43.5	1484	Yes	No



time (sec)	Axle 1 Right (%/100)	Axle 1 Left (%/100)	Axle 2 Right (%/100)	Axle 2 Left (%/100)	Axle 3 Right (%/100)	Axle 3 Left (%/100)
0.0000	0.00	0.00	0.00	0.00	0.00	0.00
0.8000	0.00	0.00	0.00	0.00	0.00	0.00
0.9000	0.25	0.25	0.25	0.25	0.25	0.25
2.0000	0.40	0.40	0.40	0.40	0.40	0.40
2.5000	0.50	0.50	0.50	0.50	0.50	0.50
3.0000	0.40	0.40	0.40	0.40	0.40	0.40
5.5000	0.00	0.00	0.00	0.00	0.00	0.00

Fig. 5.1. Available friction table for the Volvo

weight is called drag factor [16]. The drag factor is used in determining acceleration or deceleration of the vehicle.

According to the hard-brake record, the impact velocity of the Volvo was 43 mph and the velocity four seconds before the accident was 60.5 mph. The deceleration was averaged over 4 seconds and the calculated average drag factor obtained was 0.44. This initial estimate of the drag factor was adjusted iteratively in simulation to obtain a velocity profile matching the recorded one. Velocity profile was the velocities of the Volvo from time t $= -5$ to t $= 0$ where t $= 0$ is time of impact. Figure 5.1 shows the available friction entered at specified intervals. This friction table was revised from the numerous simulation iterations in order to match the velocity profile of the Volvo obtained from the simulation to that obtained from the EDR data.

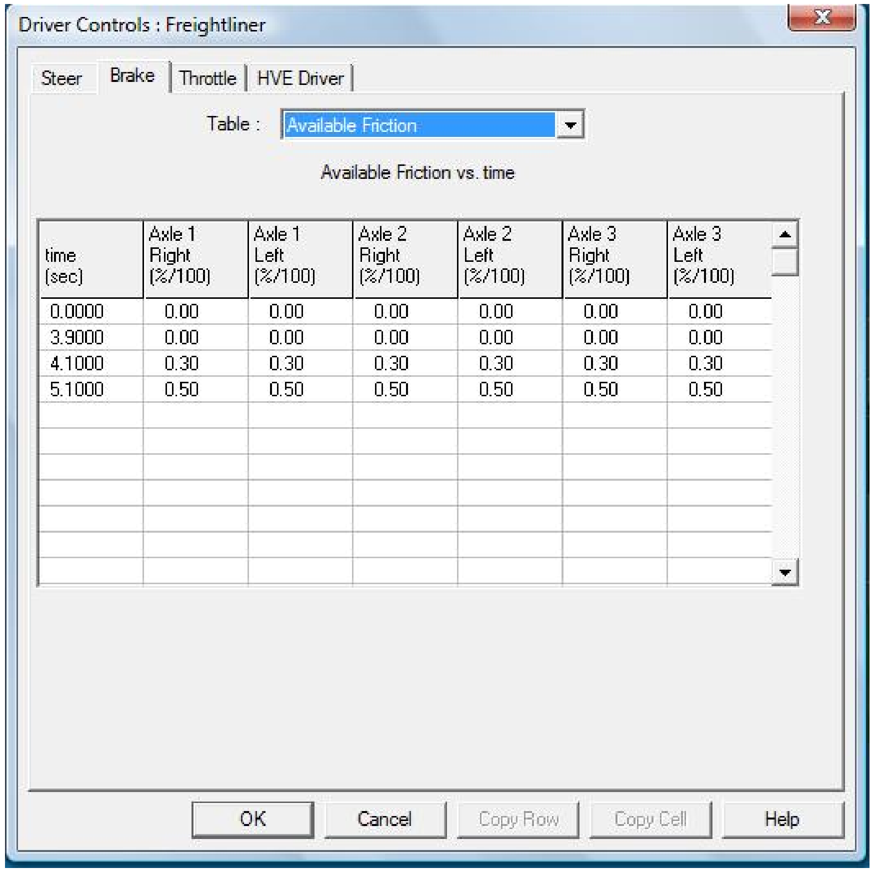
Table 5.2
EDR hard brake information for the Freightliner

Time	Vehicle Speed (mph)	Engine Speed (rpm)	Brake	Cruise
-10	59.0	1374	No	Yes
-9	59.0	1373	No	Yes
-8	59.0	1374	No	Yes
-7	58.5	1355	Yes	No
-6	58.0	1359	No	No
-5	58.0	1354	No	No
-4	58.0	1351	No	No
-3	58.0	1350	No	No
-2	58.5	1361	No	No
-1	53.5	1255	No	No
0	43.0	1010	No	No

5.2.2 Freightliner EDR-data and Its Use in Simulation

The hard brake record was also available for the Freightliner and is shown in Table 5.2. According to this data, 10 seconds prior to impact the velocity of the Freightliner was 59 mph. One second before impact the velocity was 53.5 mph and at impact it was 43 mph. At the second -2 the engine speed increases from 1350 to 1361 rpm which is consistent with the testimony of the Freightliner's driver who stated that he tried to increase the speed in order to avoid the collision [15].

The same method was used for the friction table calculation for the Volvo as was used for the Freightliner. The average drag factor for the Freightliner was 0.7. This was entered in "Available Friction" table in HVE. Numerous iterations of the simulation were performed in order to finalize the friction table to match the velocity profiles. Fig. 5.2 shows the final friction table obtained for the Freightliner.



time (sec)	Axle 1 Right (%/100)	Axle 1 Left (%/100)	Axle 2 Right (%/100)	Axle 2 Left (%/100)	Axle 3 Right (%/100)	Axle 3 Left (%/100)
0.0000	0.00	0.00	0.00	0.00	0.00	0.00
3.9000	0.00	0.00	0.00	0.00	0.00	0.00
4.1000	0.30	0.30	0.30	0.30	0.30	0.30
5.1000	0.50	0.50	0.50	0.50	0.50	0.50

Fig. 5.2. The available friction table for the Freightliner

5.2.3 Buick EDR-data and Its Use in Simulation

As shown in Table 5.3 the vehicle speed, engine speed, percent throttle and brake switch circuit status had been recorded five seconds before impact. The speed of the Buick four seconds before impact was 70 mph and slowed to 35 mph one second before impact. The brakes were on for approximately three seconds before impact. The speed at impact, obtained from the police report, was 23 mph [15].

A reference drag factor calculated for the Buick was 0.8. The friction table was revised a few times in order to match the Buick velocity profile obtained from the simulation to that obtained from the EDR data. Fig. 5.3 shows the final friction table obtained for the Buick.

Table 5.3
EDR information for the Buick

Time (s)	Vehicle Speed (mph)	Engine Speed (rpm)	% Throttle	Brake Status
-5	70	1920	0	OFF
-4	70	2048	0	OFF
-3	62	1536	0	ON
-2	47	1024	0	ON
-1	35	768	0	ON

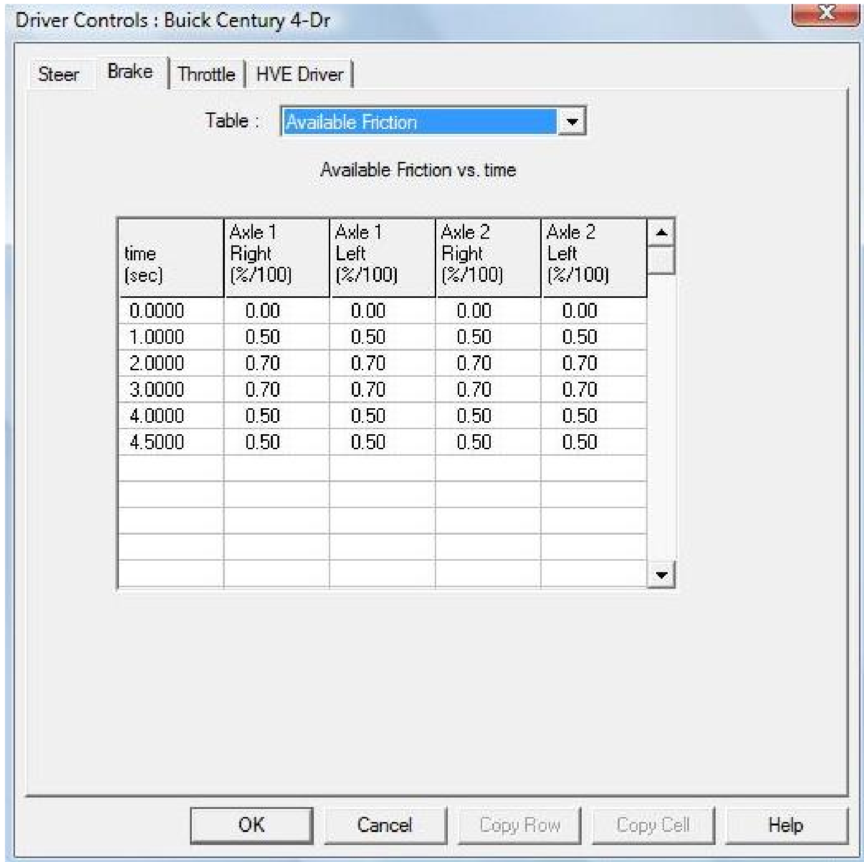


Fig. 5.3. The available friction table for the Buick

5.3 Setting Up the Simulation

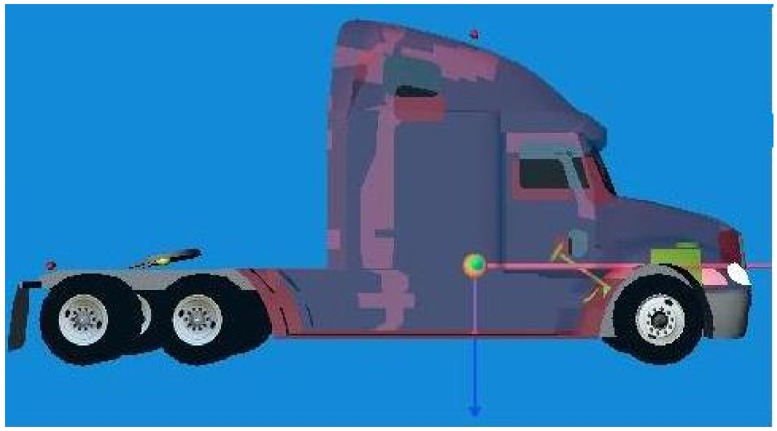
This section illustrates the set up done in HVE for the simulation and actual execution of the simulation. The first subsection gives information about the vehicles chosen from the HVE vehicle editor to obtain the best possible match with the actual vehicles, the second subsection discusses the environment used for the simulation and the third section demonstrates the actual simulation steps.

5.3.1 Description and Construction of Vehicle Models

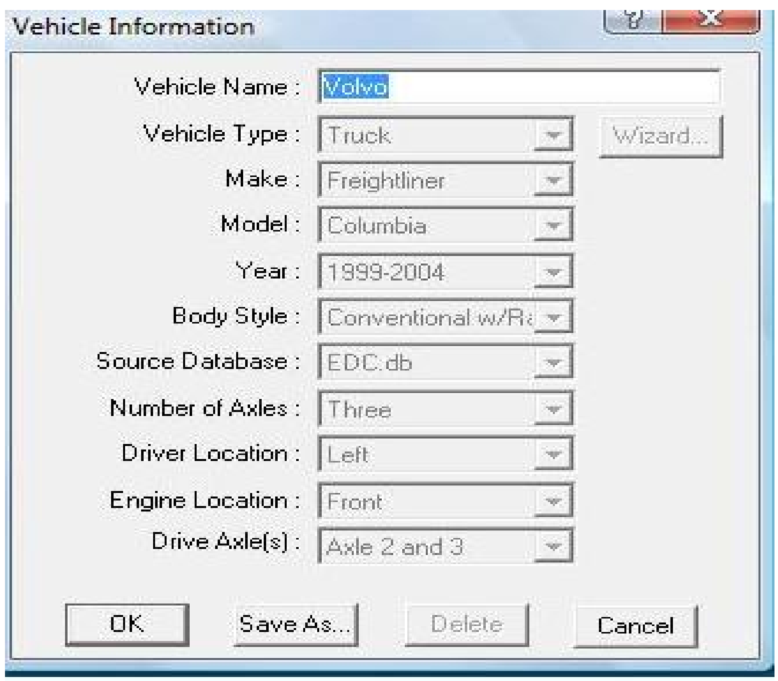
Two articulated vehicles were involved in this accident. The following subsections present the introduction and construction of these vehicles as well as the Buick using HVE vehicle editor.

The Volvo and Its Trailers The first vehicle was a Yellow 2001 Volvo cab model VNM42T and two trailers with year and make Freuhauf 1989 and Strick 1989, respectively. This specific Volvo cab was not present in HVE. So Freightliner Columbia 1999-2004 was chosen from the vehicle list. The geometry profile and specifications of the cab were selected as shown in Figures 5.4(a) and 5.4(b) on page 45.

The two trailers were each 28 feet long and had actual weights of 12,660 and 9,940 pounds, respectively. Neither was available in HVE so generic trailers were selected and their characteristics were chosen as shown in Figures 5.5(a) and 5.5(b) on page 46. The cab and the first trailer were connected using fifth wheel option available in HVE. The two trailers were connected using a dolly. The geometry profile and characteristics of the dolly are shown in Figures 5.6(a) and 5.6(b) on page 47.

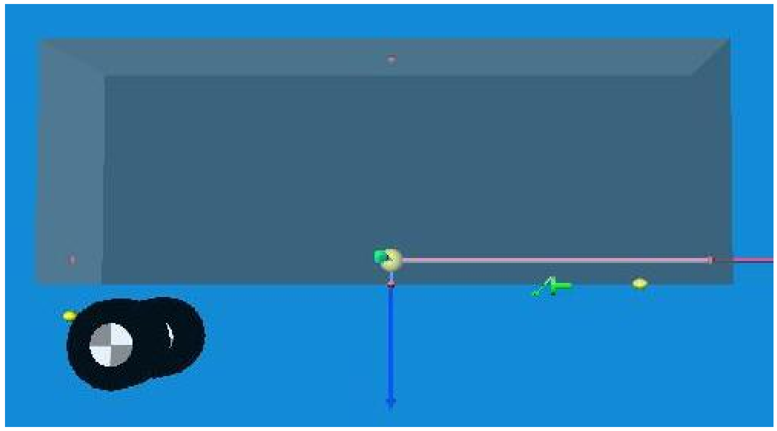


(a) Geometric profile of Volvo: The circle near the center of the vehicle indicates the center of gravity

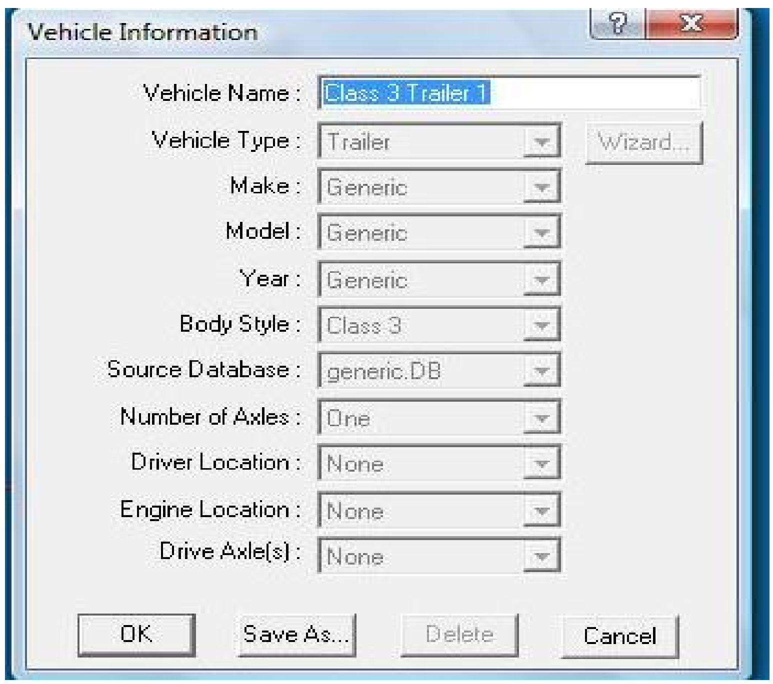


(b) Volvo tractor characteristics

Fig. 5.4. Geometry profile and characteristics of the Volvo

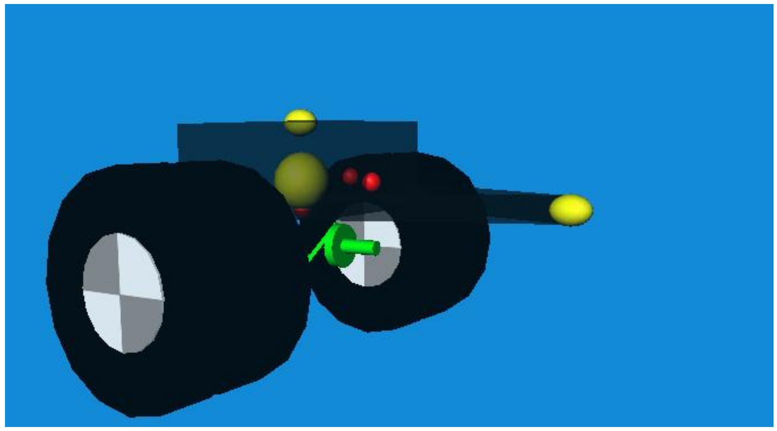


(a) Geometric profile of the trailers: The circle near the center of the vehicle indicates the center of gravity

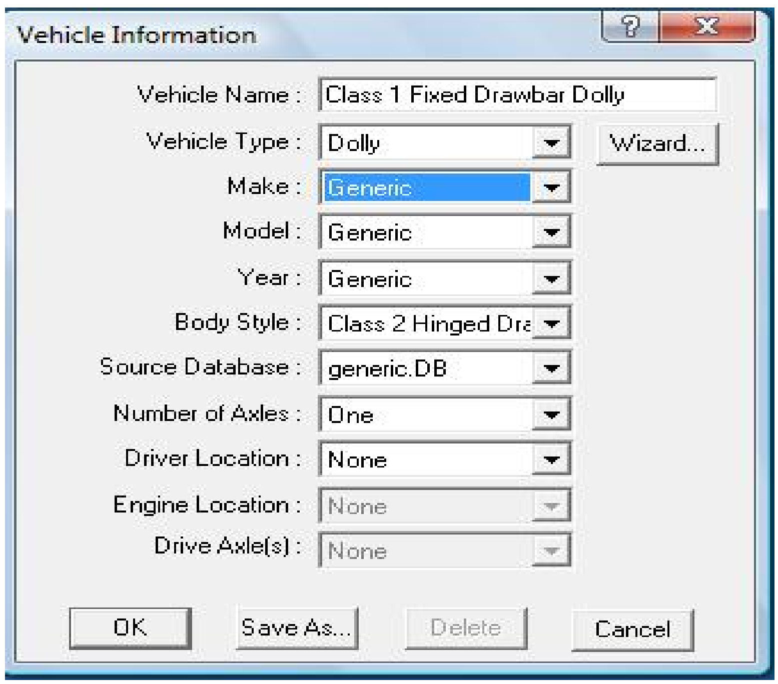


(b) Characteristics of the trailers

Fig. 5.5. Geometry profile and characteristics of the trailers



(a) Geometric profile of the dolly



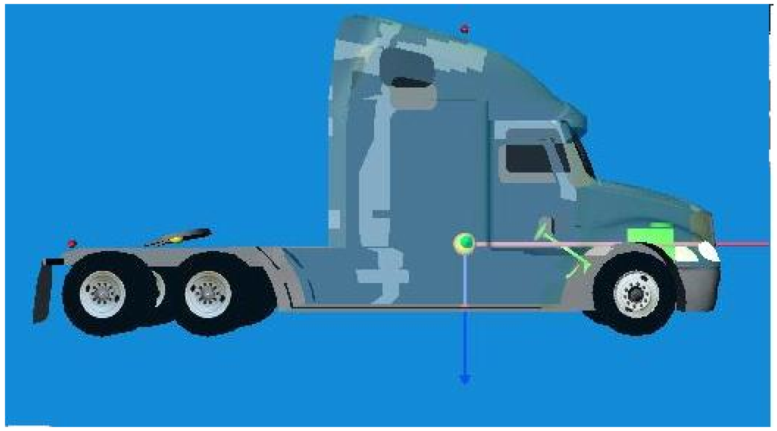
(b) Characteristics of the dolly

Fig. 5.6. Geometry profile and characteristics of the dolly

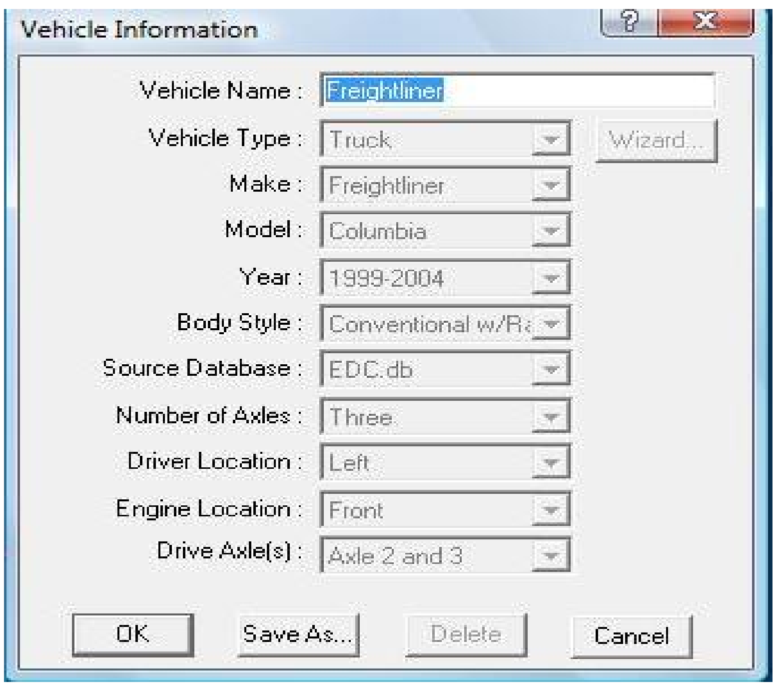
While entering articulated vehicles in the HVE event editor the cab should be selected first and then its trailers. Intermediate connections such as the dolly, connecting the trailers, should be selected in the order they are connected. For the Volvo, the selection order was Volvo cab, first trailer, dolly, and second trailer.

The Freightliner and Its Trailer The second vehicle was a Yellow Freightliner Century Class semi cab pulling one 58-foot, 1996 Great Dane trailer. The actual weights of the cab and trailer were unknown. Hence the default weights of 20,000 and 10,000 pounds were taken respectively. Figures 5.8(a) and 5.8(b) show the geometry and specifications used in HVE for this trailer.

The Buick The third vehicle involved was a tan 2003 Buick Century 4-door automobile that weighed approximately 3000 pounds. Figures 5.9(a) and 5.9(b) show the geometry and characteristics of the Buick.

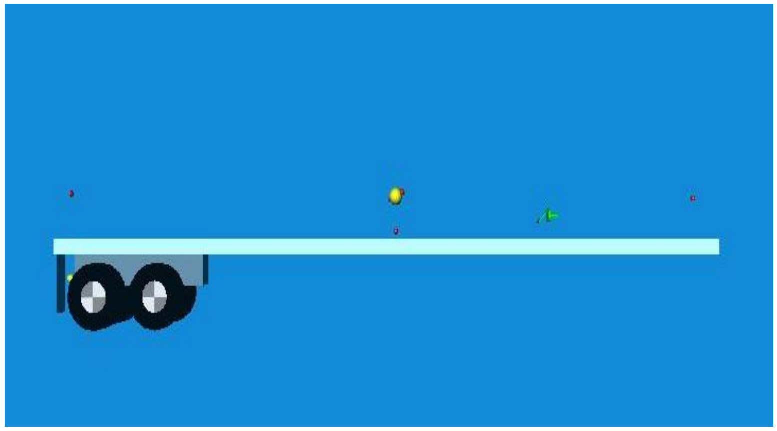


(a) Geometric profile of the Freightliner: The circle near the center of the vehicle indicates the center of gravity

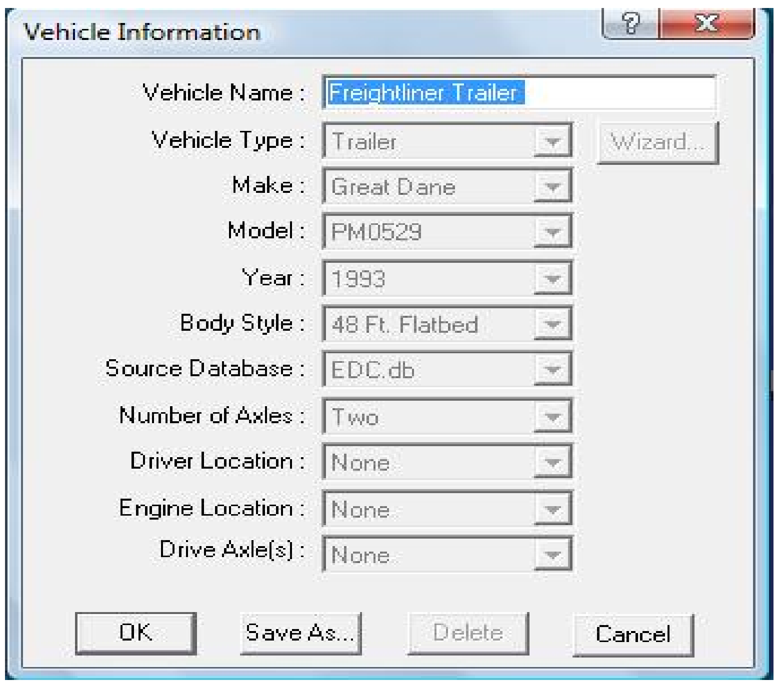


(b) Characteristics of the Freightliner

Fig. 5.7. Geometry profile and characteristics of the Freightliner



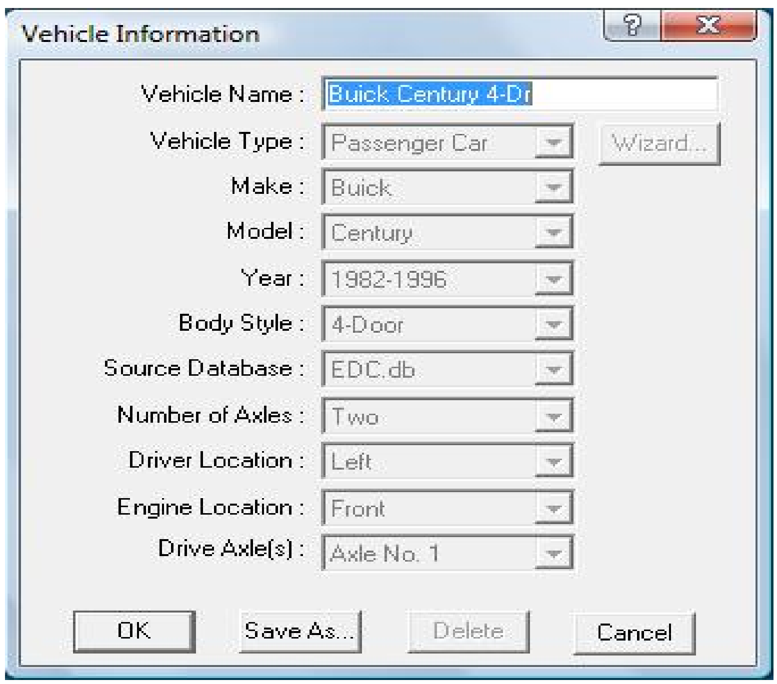
(a) Geometric profile of the Great Dane trailer: The yellow circle near the center of the vehicle indicates the center of gravity



(b) Characteristics of the trailer

Fig. 5.8. Geometry profile and characteristics of the Freightliner trailer

(a) Geometric profile of the Buick: The circle near the center of the vehicle indicates the center of gravity



(b) Characteristics of the Buick

Fig. 5.9. Geometry profile and characteristics of the Buick

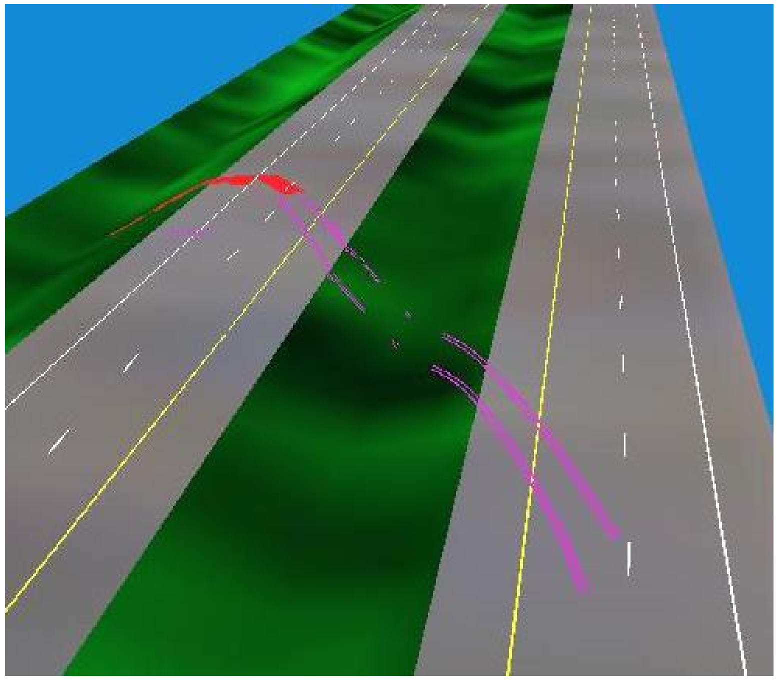


Fig. 5.10. 3D AutoCAD drawing for the three vehicle collision

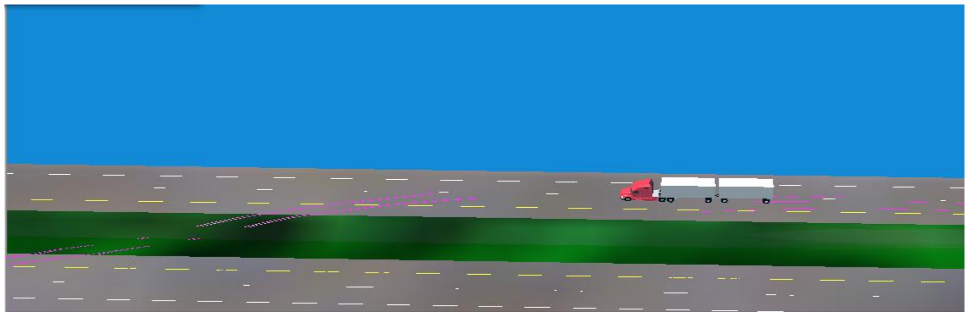
5.3.2 3D AutoCAD Environment

As with the AutoCAD environment for the previous bus-car accident, this environment was generated by Wolf. This environment gave the virtual visualization of pre-established tire marks of vehicles before and after impact, the starting and final positions of those vehicles, and the position of impact. Because it was a 3D environment, the height of the grade was also taken into account in the design. All the measurements such as the width of the lanes, the width of the grass median and the height of the grade were scaled-down versions of the real life environment. Fig. 5.10 shows the AutoCAD environment. The tire marks of the truck, which are shown in pink, indicate that the cab had entered into the grass median and come out on the wrong side of the interstate. The red marks show the final position of the truck.

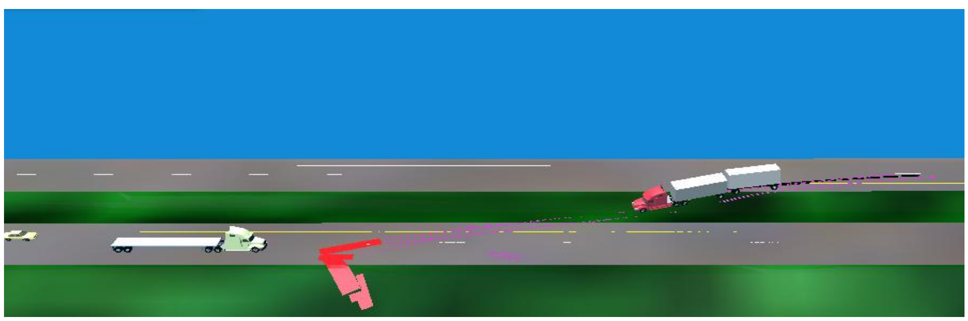
5.3.3 Simulation

This section presents the actual simulation using input parameters discussed above. The primary simulation method used for the simulation was EDSMAC4. This is illustrated in the first section. The roll-over of the trailer could not be simulated using this method. Hence another simulation method named SIMON was used to qualitatively demonstrate the roll-over of that trailer.

EDSMAC4 Analysis Figures 5.11(a) to 5.11(d), on page 53 and 54, show the sequential collision events. At the start of the simulation the vehicles were assigned their initial positions and the initial velocities. The pre-impact braking for all vehicles, as discussed in the above section, was applied. Figures 5.11(a) to 5.11(c) show the trajectory followed by the Volvo also confirm the tire-marks made by the Volvo. Figure 5.11(c) shows the collision of the Volvo and the Freightliner. After the collision with the Freightliner the first trailer of the Volvo turns over on the Buick. But this turn over could not be shown in EDSMSC4 method, because in this method the simulation is terminated if the contact between tires and the road is lost.

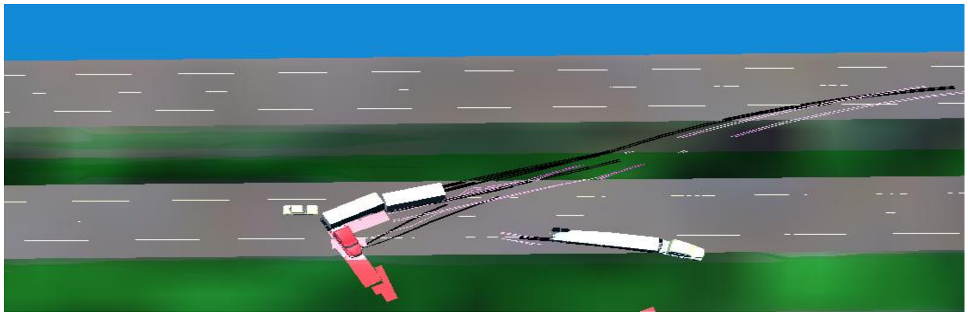


(a) The initial position of the Volvo five seconds before the accident with the speed of 60.5 mph



(b) The Volvo loses control and starts going out of the lane, into the grass median

(c) The Volvo continues onto the wrong side of the interstate and hits the Freightliner



(d) The first trailer of the Volvo is about to turn over on top of the Buick

Fig. 5.11. The sequential simulation for three vehicle accident

SIMON Analysis The SIMON method was used to show the qualitative simulation of the trailer roll-over. The initial positions and velocities of the vehicles were same as those used in the EDSMAC4 method. Figure 5.12 shows the roll-over of the first trailer of the Volvo on the Buick.

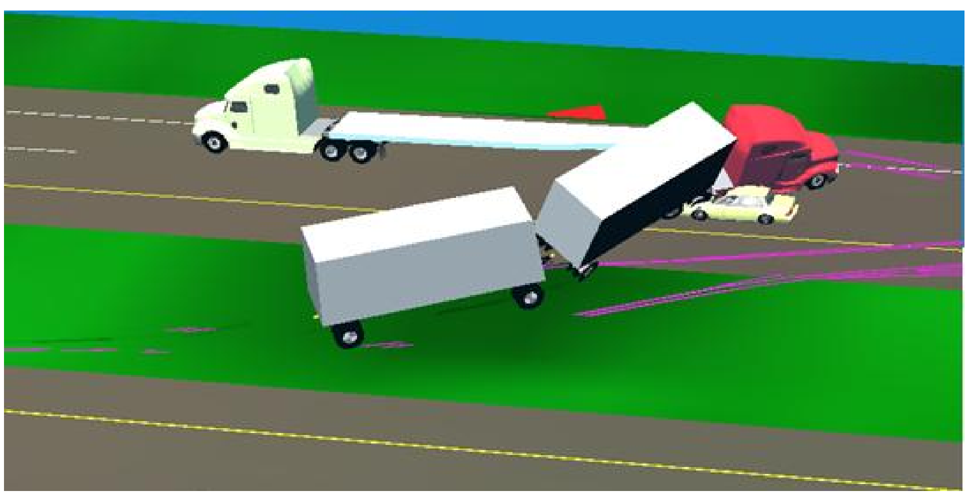


Fig. 5.12. The roll-over of the truck using SIMON method

5.4 Results of the Simulation

Table 5.4 shows the simulated velocity profiles and EDR-recorded velocity profiles for all three vehicles using the EDSMAC4 method. According to the table the simulated and EDR-recorded data are consistent with each other. At impact the velocity of the vehicles could be any velocity in the range of velocities from -1 seconds to 0 seconds. Therefore, the impact velocity of the Volvo could be any velocity between 53 and 43.5 mph. The impact velocity observed in the simulation was 47.61 mph. The impact velocity of the Freightliner would be in the range 53.5 to 43 mph. Its simulated impact velocity was 53 mph. The velocity of the Buick at the impact was not available from the EDR data. It was calculated by the respective accident re-constructionists using drag factor obtained from the velocity profile of the Buick before the impact [15]. As the simulation was terminated when the trailer started to roll over the velocity of the Buick at impact was not obtained. The SIMON simulation method was used to show the roll-over of the trailer.

Table 5.4
The velocity profiles of all the vehicles obtained from HVE

Time	Volvo HVE	EDR	Freightliner HVE	EDR	Buick HVE	EDR
(sec)	(mph)		(mph)		(mph)	
-4	60.5	60	58	58	70	70
-3	59.67	59.5	58	58	65	62
-2	56.99	57.5	58	58.5	46.39	47
-1	53.91	53	57.01	53.5	36.94	35
0	47.61	43.5	53	43	23	not available

5.5 Summary and Conclusion

The accident involving two trucks and one car was simulated using the EDR data. The 3D Auto-CAD environment representing the physical evidence of the accident was available. Approximate initial and impact speeds of all the vehicles were inferred from the EDR data. Using these input parameters the accident was simulated using the EDSMAC4 method in HVE and the existence of the tire-marks left by the Volvo on the road was verified. HVE environment editor had an option to select environmental conditions such as wind and rain. According to the Volvo's driver's testimony one of the reasons he lost control was the wind. An attempt was made to observe the effect of the wind on the movement of the Volvo, but it was found that the effect of the environmental changes on the simulation cannot be tested in HVE. The qualitative simulation of the roll-over of the trailer was performed using the SIMON simulation method.

In the bus-car accident the impact velocity and initial velocities were estimated using conservation of momentum and energy. For the accident discussed in this chapter, the at-impact and pre-impact velocities were directly obtained from the EDR data. So the EDR was useful in obtaining approximate estimate of these velocities. These EDR data were also used to verify the driver's testimony. These EDR data were verified by the Indiana state police using available real-life evidence.

6. INTERSECTION COLLISION

This chapter introduces the collision of a left-turning car with an oncoming car. The vehicles involved in this accident had EDR data. The EDR data for the turning car included physical parameters such as steering angle, yaw rate and lateral acceleration. The purpose of the simulation was to simulate the turning car's trajectory based on these input data. The approximate trajectory and turning angle of the vehicle was available from the police report [17]. The simulation results matched qualitatively with the evidence.

6.1 Accident Scenario

A 2010 Ford Escape transporting one passenger was traveling southbound on a four-lane road. The Ford Escape entered in the left turn lane and, while trying to make a left turn, got hit by the oncoming 2008 Dodge Charger. The EDR data were available for both the cars. According to that data, the speed of the Ford at impact was 11.8 mph and that of the Dodge was approximately 37 mph. The initial speeds of the Ford and the Dodge were 21.7 mph and 45 mph, respectively. These speeds were recorded five seconds before impact.

6.2 Preliminary Calculations Using EDR Data

The EDRs of both vehicles resided in the Airbag Control Modules (ACMs). Because both of them were Ford's EDRs, they were referred to as the Restraint Control Modules (RCMs). Different physical parameters such as speed, lateral acceleration and yaw rate associated with the vehicles at the time of impact were available in the

EDR data. The following sections discuss the EDR data available for each vehicle and their use in the simulation.

6.2.1 EDR Data for the Ford Escape

The data were available five seconds before impact and recorded at the rate of ten samples/sec. These data contained Steering Wheel Angle, Lateral Acceleration, Stability Control, Longitudinal Acceleration, Stability Control, Yaw Rate, and Stability Control Roll Rate as shown in Figure 6.1 on page 75.

Table 6.1 shows the selected parameters, which were used for the analysis. Yaw rate and lateral acceleration were averaged over 0.5 second intervals. According to the EDR data, the speed of the Ford five seconds before impact was 21.7 mph and at impact 11.8 mph.

Table 6.1
EDR information for the Ford

Time (sec)	Vehicle Speed (mph)	Yaw Rate (deg/0.5sec)	Lateral Acceleration (g)	Brake light ON/OFF
−5	21.7	0.00	0.08	ON
−4.5	20.5	0.00	0.00	ON
−4	18.5	0.28	0.025	ON
−3.5	18.0	0.20	0.075	ON
−3	16.8	-1.00	0.152	ON
−2.5	15.5	-7.52	0.184	ON
−2	14.9	-11.00	0.262	ON
−1.5	14.9	-18.4	0.367	ON
−1	14.9	-26.00	0.311	OFF
−0.5	11.8	-30.00	0.471	ON
0	11.8	-42.00	0.296	OFF

Pre-Crash Data -5 to 0 sec [10 samples/sec] (First Record)

Times (sec)	Steering Wheel Angle (degrees)	Stability Control Lateral Acceleration (g)	Stability Control Longitudinal Acceleration (g)	Stability Control Yaw Rate (deg/sec)	Stability Control Roll Rate (deg/sec)
- 5.0	-500.6	0.092	-0.273	0.01	-2.5
- 4.9	-501.5	0.142	-0.187	0.13	-1.12
- 4.8	-501.5	0.03	-0.009	0.63	1.62
- 4.7	-501.4	0.013	-0.171	0.01	-1.25
- 4.6	-501.4	0.018	-0.221	-0.86	1.12
- 4.5	-501.4	0.019	-0.155	-0.11	3.37
- 4.4	-501.3	-0.044	-0.118	0.01	2.5
- 4.3	-501.1	0.013	-0.132	-0.24	1.75
- 4.2	-501.1	0.01	-0.157	-0.61	2.62
- 4.1	-501.1	0.027	-0.142	-0.49	1.25
- 4.0	-501.1	0.023	-0.127	-0.36	0.0
- 3.9	-501.0	0.034	-0.137	-0.86	0.25
- 3.8	-500.0	0.032	-0.174	-0.11	-0.25
- 3.7	-499.2	0.055	-0.207	-0.24	-0.25
- 3.6	-497.9	0.064	-0.169	0.51	0.5
- 3.5	-494.9	0.086	-0.184	0.76	0.25
- 3.4	-490.4	0.098	-0.192	1.51	1.25
- 3.3	-485.5	0.075	-0.197	2.76	1.37
- 3.2	-480.3	0.137	-0.176	4.51	1.12
- 3.1	-476.3	0.159	-0.137	5.88	0.5
- 3.0	-473.0	0.155	-0.118	7.13	-0.75
- 2.9	-471.5	0.154	-0.095	7.01	-0.62
- 2.8	-470.8	0.149	-0.081	7.26	-0.12
- 2.7	-469.7	0.145	-0.098	7.63	-1.0
- 2.6	-467.2	0.172	-0.071	8.63	-1.25
- 2.5	-462.8	0.173	-0.127	8.76	-1.37
- 2.4	-456.5	0.19	-0.145	9.88	2.62
- 2.3	-450.7	0.241	-0.152	11.13	1.37
- 2.2	-445.5	0.248	-0.127	12.26	0.62
- 2.1	-439.9	0.27	-0.127	13.63	-1.5
- 2.0	-432.8	0.243	-0.152	15.76	-1.25
- 1.9	-427.7	0.269	-0.11	17.38	-1.75
- 1.8	-422.5	0.279	-0.11	18.51	-0.5
- 1.7	-416.2	0.289	-0.11	20.13	0.0
- 1.6	-408.0	0.362	-0.098	21.01	-1.87
- 1.5	-399.3	0.372	-0.118	23.26	-1.12
- 1.4	-391.5	0.401	-0.135	26.63	-0.25
- 1.3	-389.5	0.413	-0.073	27.38	0.0
- 1.2	-390.8	0.302	-0.339	28.38	-7.12
- 1.1	-391.3	0.27	-0.702	24.88	-9.25
- 1.0	-386.4	0.302	-0.458	26.26	-8.75
- 0.9	-369.9	0.319	-0.108	27.38	2.37
- 0.8	-349.2	0.363	-0.145	28.88	1.75
- 0.7	-327.3	0.444	-0.204	31.51	2.25
- 0.6	-308.3	0.528	-0.194	36.76	3.37
- 0.5	-312.7	0.499	-0.127	42.51	1.12
- 0.4	-315.3	0.383	-0.145	43.51	-5.0
- 0.3	-318.3	0.501	-0.152	40.88	-7.0
- 0.2	-331.5	0.319	-0.076	40.26	0.87
- 0.1	-349.9	0.269	0.048	39.26	-3.62
0.0	-367.8	0.296	0.115	33.88	-0.75

Fig. 6.1. Steering angle and lateral acceleration data for the Ford

6.2.2 EDR Data for the Dodge Charger

The EDR data for the Dodge Charger is shown in Table 6.2. Some selected parameters from the actual EDR data are shown here.

Table 6.2
EDR information for the Dodge

Time	Engine	Vehicle Speed	Throttle
(sec)	(rpm)	(mph)	(% Full)
−0.5	1408	43	5.5
−0.4	1376	42	5.1
−0.3	1280	39	5.1
−0.2	1184	38	4.7
−0.1	1152	37	4.7
0	1152	37	4.7

6.2.3 Ford Escape Trajectory Estimation Using EDR Data

The analysis of the EDR data was performed in order to reconstruct the turning path of the Ford. The parameters available from the EDR data were steering angle, lateral acceleration and yaw rate. The aim of the analysis of these parameters was to recreate the trajectory and turning angle of the Ford similar to those shown in Figure 6.2. The following sections discuss the path reconstruction from each of the these parameters.

Steering Angle The steering angle data were available for a total of five seconds before impact, recorded at the rate of ten samples/sec. Instead of using this large amount of data, it was averaged for every 0.5 second interval. This averaged data was entered into the steering angle table in HVE, but with that approach the simulation results did not match with the real-life evidence. For example,

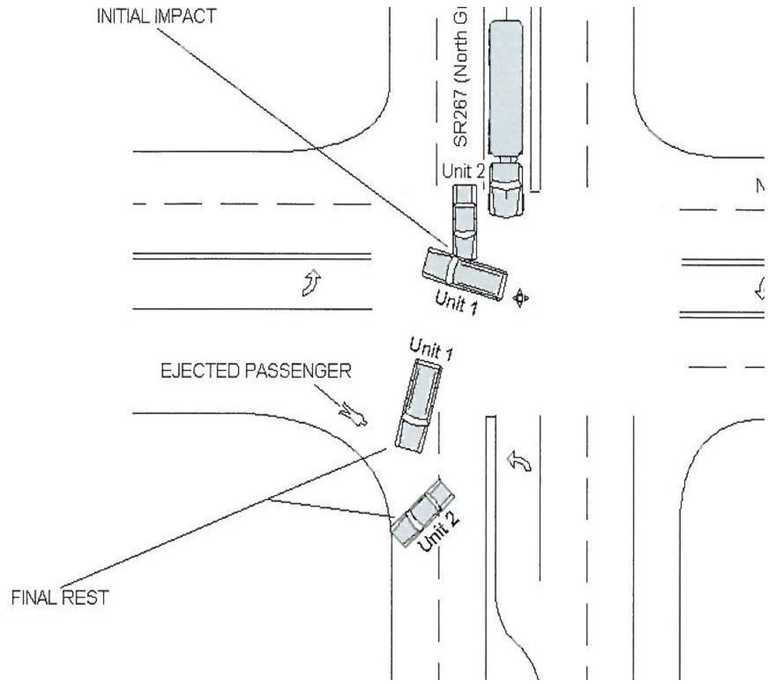


Fig. 6.2. The intersection accident design obtained from the police report

the simulation showed the car's trajectory as a U-turn along with significant skid marks as shown in Figure 6.3. Both of them were not observed in the real-life evidence. Therefore, lateral acceleration data were used to obtain the Ford's trajectory.

Lateral Acceleration Lateral acceleration was available for five seconds before the impact, recorded at the rate of ten samples/sec as shown in Figure 6.1. This was averaged for every 0.5 second interval. The radius of curvature and turning angle were calculated using this acceleration. Using these two values, the curve was plotted in the Solid-works design tool as shown in Figure 6.4.

The path obtained by the lateral acceleration matched that of the real-life scenario. Using this path estimation, the sensitivity study was performed for the steering angle. As shown in Figure 6.4 the Ford traveled in a straight-line path at the beginning so the steering angle should be approximately 0 deg. This data contradicted the EDR-recorded steering angle data, which was -500 deg. Thus, to make the steering angle

Fig. 6.3. Escape trajectory using original steering angle profile

data more realistic, the -500 deg. angle was treated as 0 deg. and the rest of the steering angles were corrected by the same correction factor. The trajectory of the Escape using this scaling is shown in Figure 6.5. With this scaling the path trajectory of the Ford was improved, but still had qualitative error in the turning angle of the Ford. The yaw rate data were also available. The yaw-angle data were estimated from the yaw-rate data and were entered in the driver control parameter named "Steer at Axle" in HVE. By using the yaw-rate data the same trajectory as shown in Figure 6.5 was obtained. So to improve the turning angle further and to match it qualitatively with that shown in Figure 6.2, the steering angle was scaled by 50% and the Ford's trajectory was obtained as shown in Figure 6.6 which was in good agreement with the real-life evidence.

6.2.4 Braking Friction Calculation for the Ford

According to the EDR data, the Ford's speed was 21.5 mph five seconds before the accident. One second before the accident, the speed was 14.9 mph and at impact

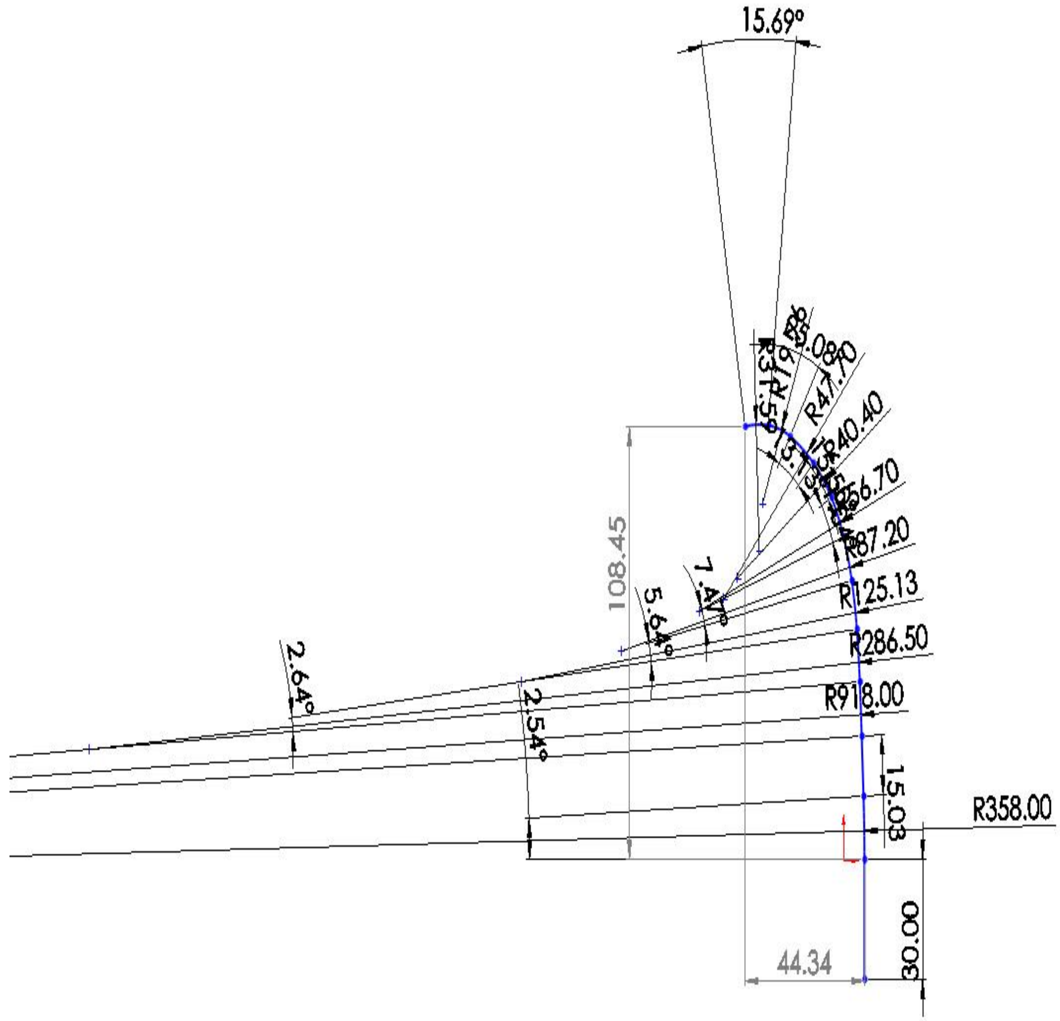


Fig. 6.4. Escape trajectory reconstruction using lateral acceleration

it was 11.8 mph. The estimated average drag factor (acceleration force divided by gravitational force) to reduce the speed from 21.7 mph to 11.8 mph in five seconds was 0.2. After numerous iterations of the simulation, the friction table was obtained for the Ford as shown in Figure 6.7.

Fig. 6.5. Escape trajectory after steering angle inversion

Fig. 6.6. Escape trajectory for scaled steering-angle data

time (sec)	Axle 1 Right (%/100)	Axle 1 Left (%/100)	Axle 2 Right (%/100)	Axle 2 Left (%/100)
0.0000	0.18	0.18	0.18	0.18
2.5000	0.18	0.18	0.18	0.18
3.0000	0.00	0.00	0.00	0.00
4.0000	0.00	0.00	0.00	0.00
4.5000	0.80	0.80	0.80	0.80
4.5100	0.00	0.00	0.00	0.00

Fig. 6.7. Available friction for the Ford Escape

6.2.5 Braking Friction Calculation for the Dodge

Five seconds before the accident, the speed of the Dodge was 45 mph. Its speed was 44 mph 0.5 seconds before the accident, and at impact was 37 mph. The estimated average drag factor to reduce the speed from 44 mph to 37 mph in 0.5 seconds was approximately 1. After numerous iterations of the simulation, the friction table obtained for the Dodge is as shown in Figure 6.8.

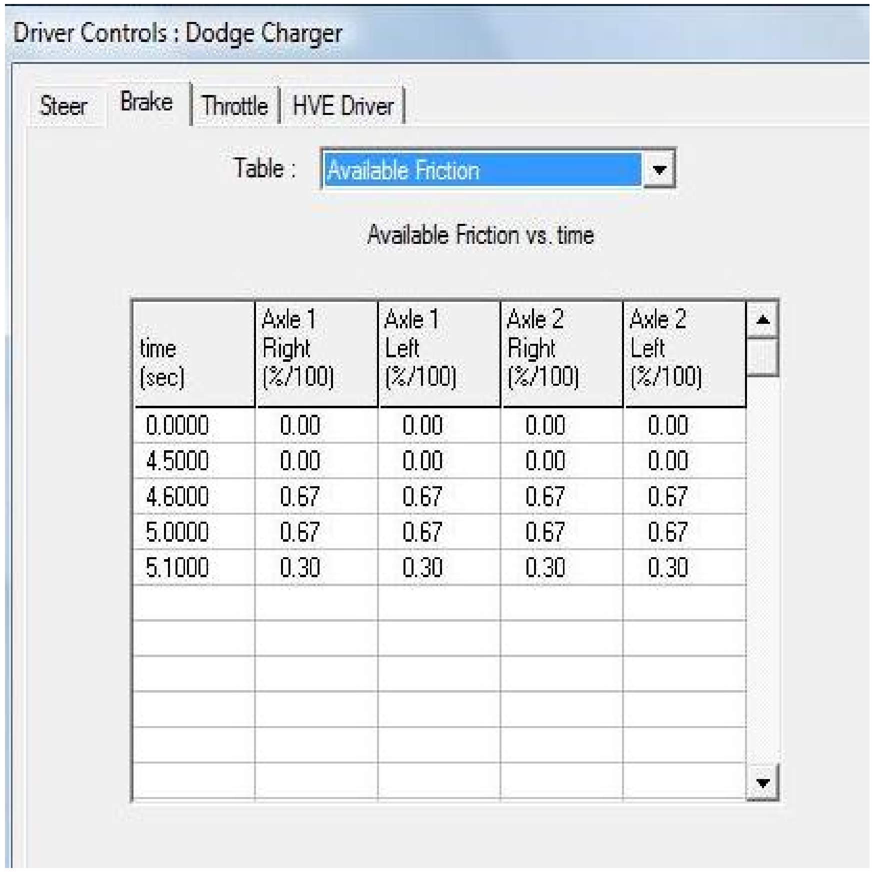


Fig. 6.8. Available friction for the Dodge Charger

6.3 Setting Up the Simulation

This section illustrates the steps taken to set up done in HVE for the simulation and actual execution of the simulation. The first subsection gives information about the vehicles chosen from the HVE vehicle editor to match, as closely as possible, the actual vehicles, the second subsection discusses the environments used for the simulation and the third section demonstrates the actual simulation steps.

6.3.1 Description and Construction of Vehicle Models

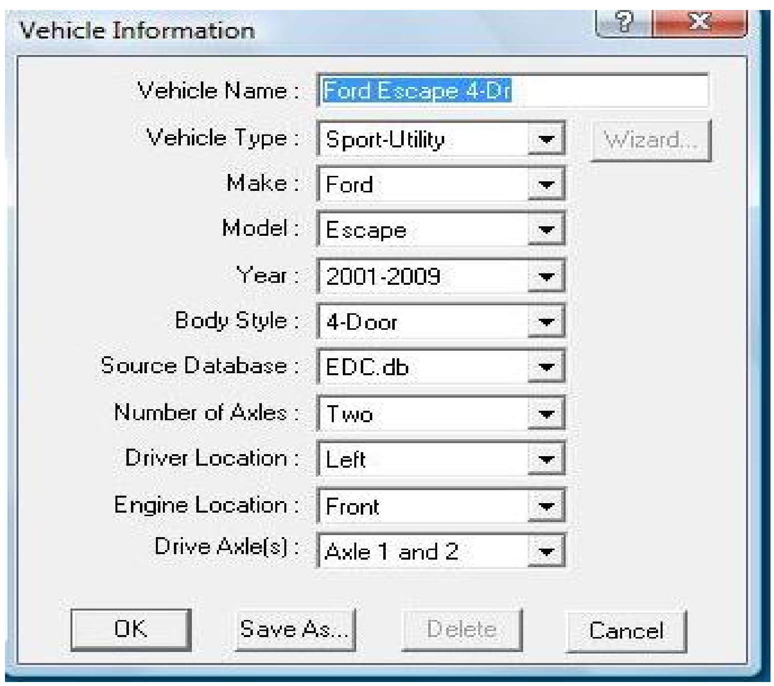
This section provides background information about the vehicles and also discusses the recreation of these vehicles in the simulator.

The Ford Escape The turning vehicle was the 2010 Ford Escape. In the HVE database, the 2010 Ford Escape was not available. The closest match, a 2001-2009 Ford Escape was selected. The geometric profile and characteristics of the Ford are as shown in Figures 6.9(a) and 6.9(b) on page 69. The steering ratio for the Escape was 17.5. So the HVE steering ratio was changed from the default ratio to this new ratio.

The Dodge Charger The oncoming vehicle, the 2008 Dodge Charger, was also not available in the HVE database. A 2000-2007 Ford Taurus was selected, which had physical characteristics, such as stiffness coefficient, similar to those of the 2008 Dodge Charger. Figures 6.10(a) and 6.10(b), on page 70, show the geometric profile and the specifications chosen for the Dodge Charger from the HVE vehicle editor.

The performance of the brakes of this selected vehicle was tested. The braking characteristics of the Dodge were available from the Expert AutoStats data [18]. Expert Autostats is a program which provides information about a vehicle, such as dimensions, braking and steering. This braking data indicated that the speed of the vehicle could be reduced from 60 mph to 0 mph, in 3.1 seconds, with -28 ft/sec^2 acceleration. The braking data were verified in HVE by applying full braking at 60 mph. As shown in Table 6.3 the braking characteristics obtained by the simulation were in agreement with those from the AutoStats reports.

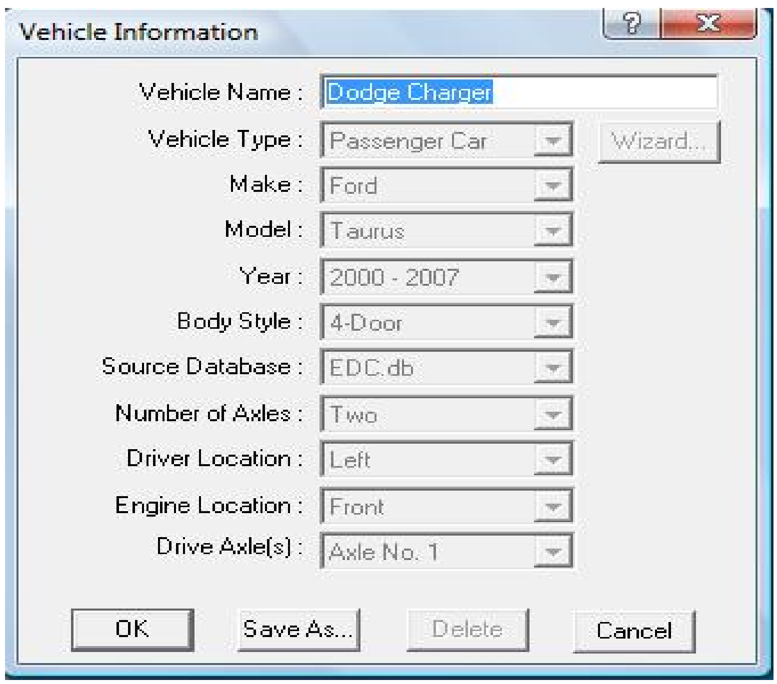
(a) Geometric profile of the Ford Escape: The circle near the center of the vehicle indicates the center of gravity



(b) Characteristics of the Ford Escape

Fig. 6.9. Geometry profile and characteristics of the Ford Escape

(a) Geometric profile of the Ford Taurus: The circle near the center of the vehicle indicates the center of gravity



(b) Characteristics of the Ford Taurus

Fig. 6.10. Geometry profile and characteristics of the Ford Taurus

Table 6.3
Braking characteristics verification for the Dodge

Braking Characteristics	AutoStats	HVE Simulation
Braking Distance (ft)	138	137
Braking Time (sec)	3.1	3.06

6.3.2 Environment

The environment required for this accident was an intersection between four lane roads with left turn lanes. A customized environment having the aerial view of the actual accident site was created and used to simulate the accident in 2D. A built-in intersection environment having four lanes without left turn lane was available in the HVE environment editor. It was used to simulate the accident in 3D. The following sections give a brief introduction about each of these environments.

4x4Intersection.h3d The standard environment, which was a built-in environment in HVE, was used for performing the simulation in 3D. Figure 6.11 shows the built-in intersection environment used for the simulation.

Customized Environment The environment needed for the simulation in 2D was downloaded from the Indiana Spatial Data Portal web site. This site provides aerial view by county. The county and approximate location of the accident were first observed using Google Earth, and that location was downloaded from the Indiana Data Portal web site. For the download, there were two scaling options - 12 inch/pixel and 6 inch/pixel. The first option was chosen and this image was stored in the EnvStructures folder, which resided in the environment database in HVE. The image was further processed and converted into a .h3d file, the standard format for environments, using the HVE-environment editor. Figure 6.12 shows this processed aerial view of the actual accident location.

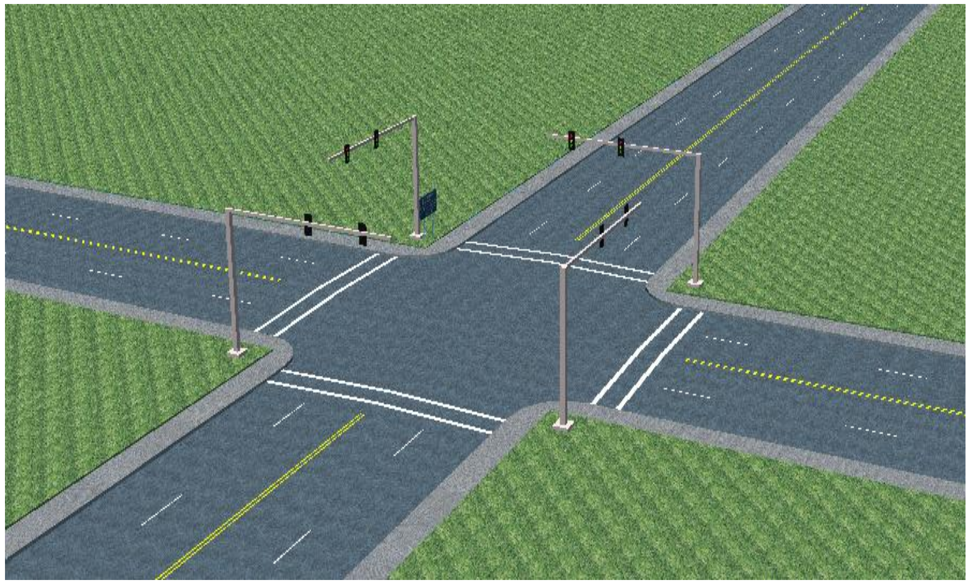


Fig. 6.11. In-built intersection environment

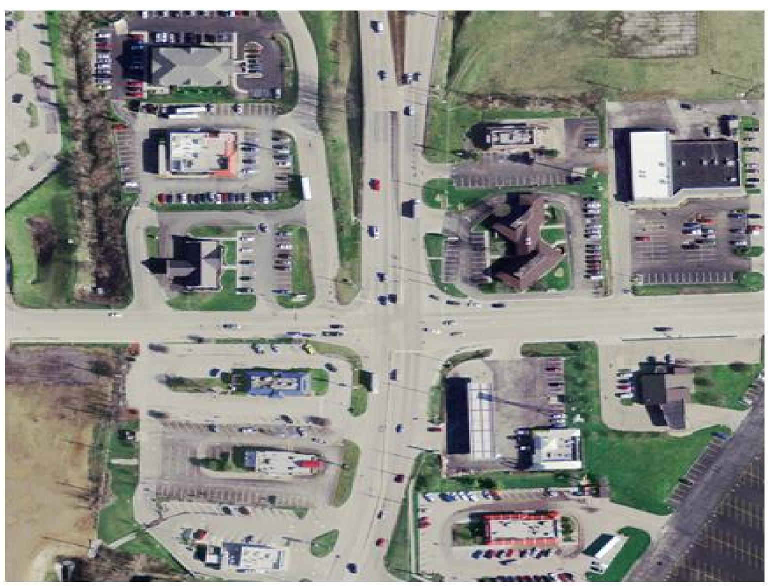


Fig. 6.12. Aerial view of the actual accident place

6.3.3 Simulation

Using the path reconstructed from the EDR data, the event was executed in HVE-2D using the customized environment. Figure 6.13 shows the path traveled by both vehicles before and after the collision. Tire marks shown in the figure are not skid marks. They are drawn in order to show the trajectories of both vehicles.

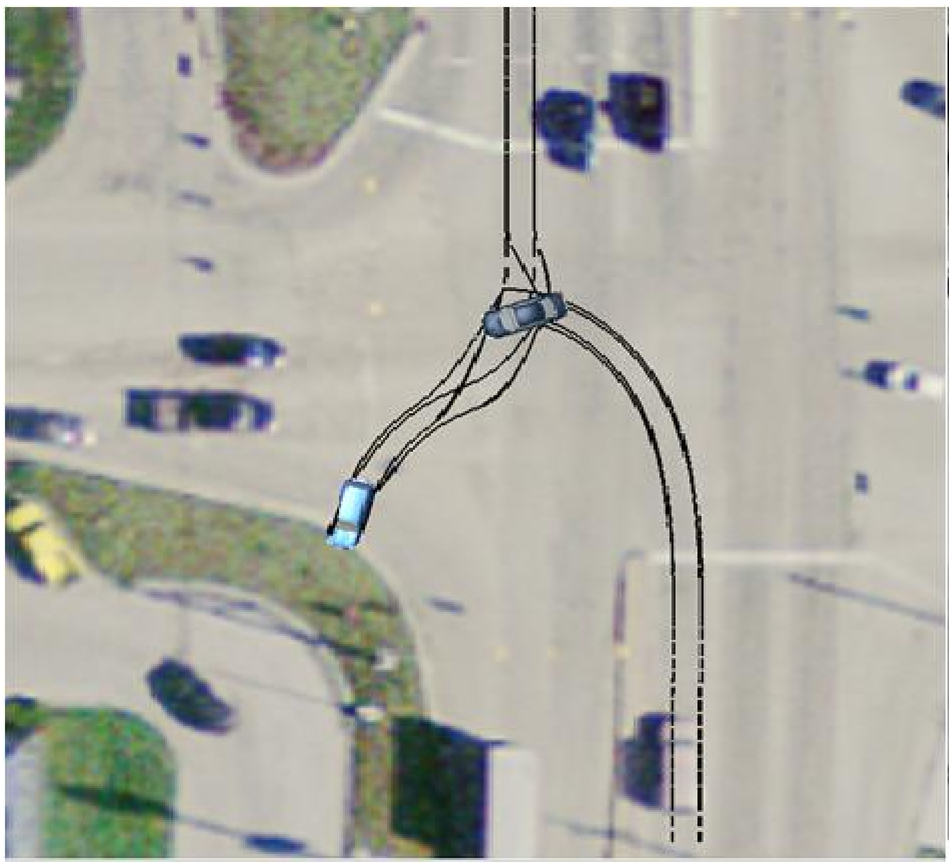
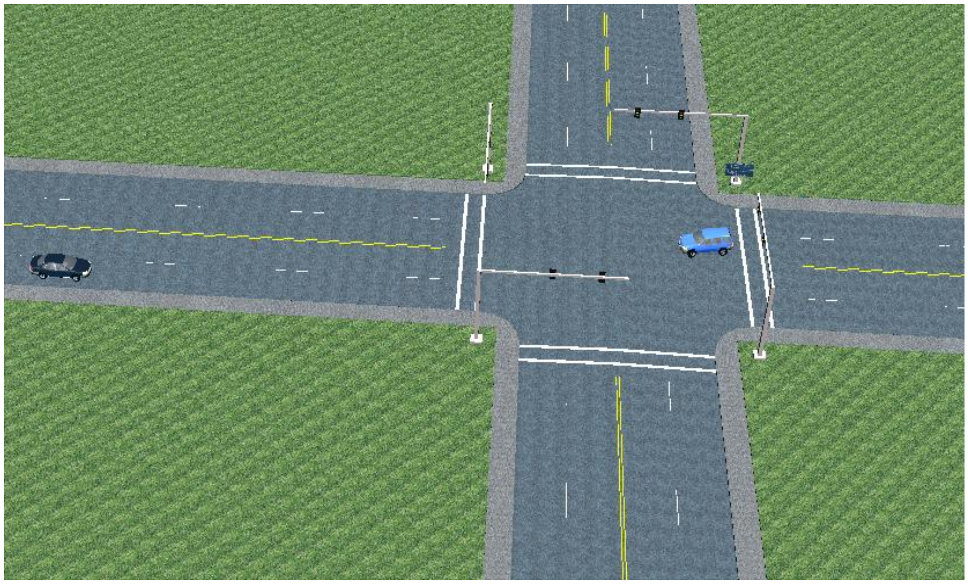
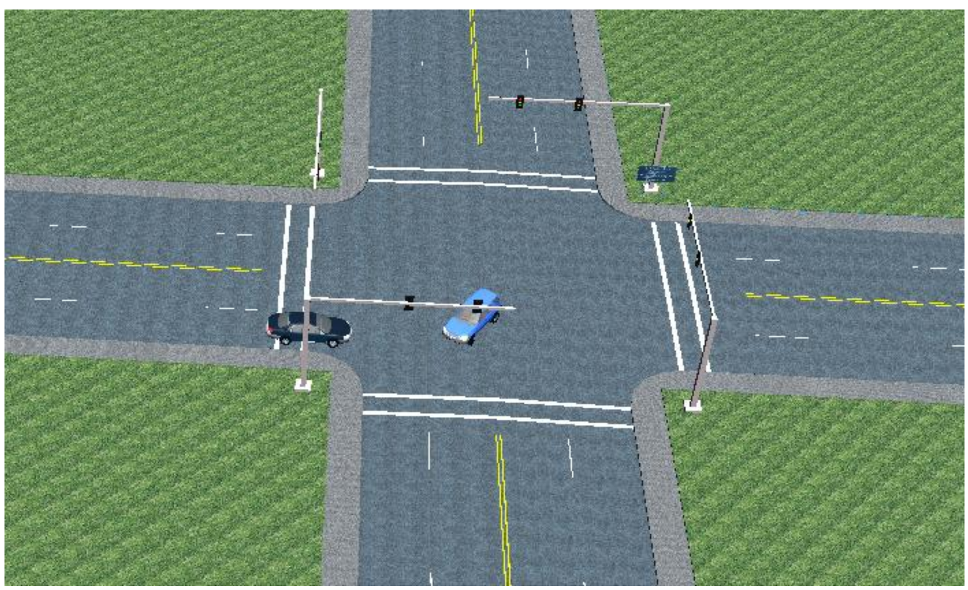


Fig. 6.13. The paths followed by the vehicles

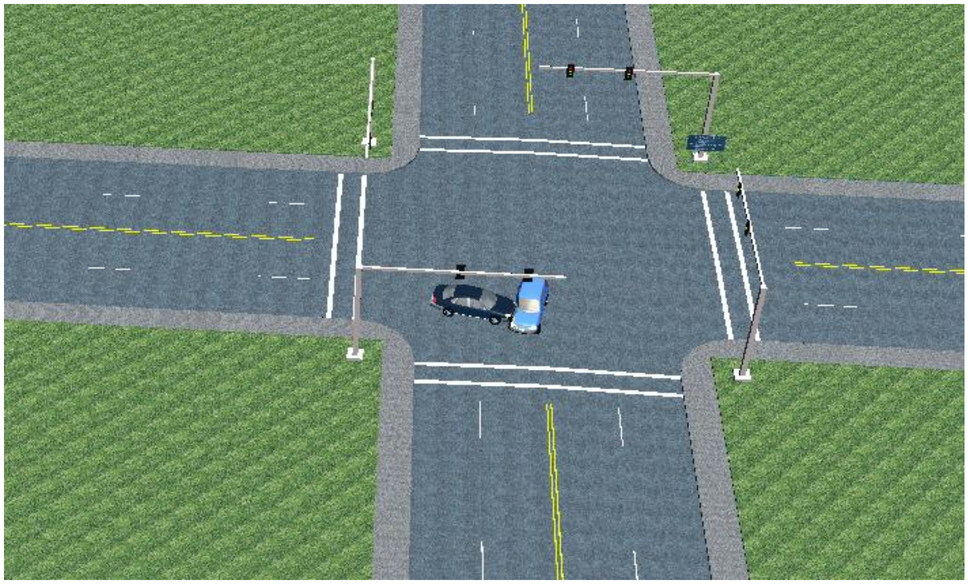
Figures from 6.14(a) through 6.14(d), on pages 74 and 75, show the sequential events in this accident from a different angle. This event is simulated using the 3D version of HVE.



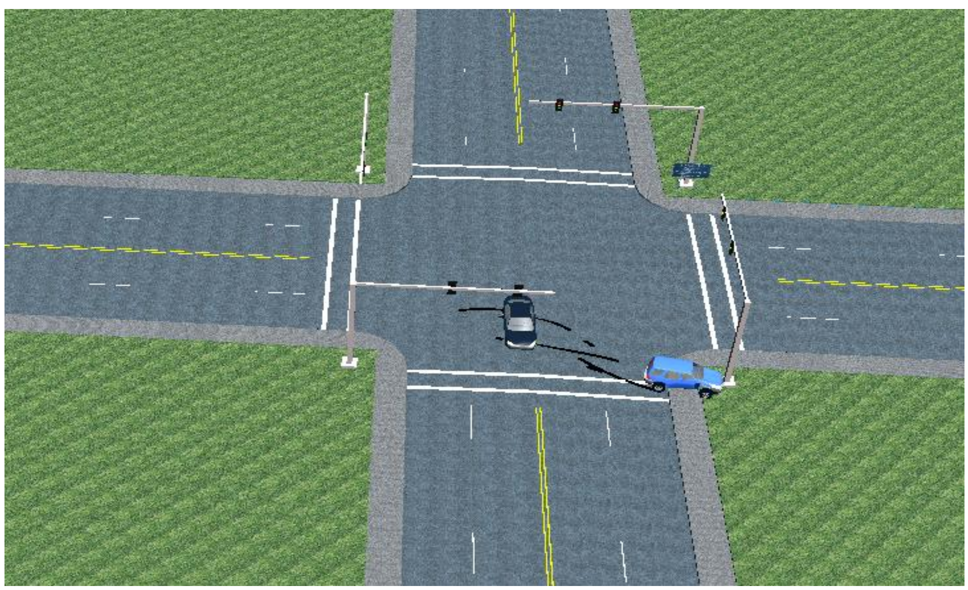
(a) The Ford Escape begins to make a turn



(b) The Dodge enters the intersection



(c) The Dodge collides with the Ford



(d) The final positions of both vehicles

Fig. 6.14. The sequential simulation events for the intersection accident

Table 6.4
Velocity profile comparison for the Dodge

Time	EDR Speed	HVE Speed
(sec)	(mph)	(mph)
−0.5	44	43.37
−0.4	43	42.12
−0.3	42	40.87
−0.2	39	39.62
−0.1	38	38.37
0	37	37.12

Table 6.5
Velocity profile comparison for the Ford

Time	EDR speed	HVE speed
(sec)	(mph)	(mph)
−5	21.7	21.7
−4	18.6	18.91
−3	16.8	16.55
−2	14.9	14.95
−1	14.9	14.95
0	11.8	11.9

6.4 Results of the Simulation

The velocity profile comparisons for the Dodge and the Ford are presented in Tables 6.4 and 6.5, respectively show that the simulated and EDR-recorded velocity profiles are consistent. Also the estimated trajectory of the Ford was achieved while maintaining its velocity profile in agreement with that of the EDR data. While estimating the trajectory of the Ford by using only the EDR data, the Dodge had to be placed in the driving rather than the passing lane, as reported in the police report, to obtain the observed damage [17].

6.5 Summary and Conclusion

The collision of the two cars at the intersection is simulated in this chapter. The EDR data were available for both the vehicles. Using input parameters such as lateral acceleration, steering angle and pre-impact velocities available for the Ford, its trajectory was predicted using the EDSMAC4 simulation method. The lateral acceleration data were used to estimate the trajectory of the Ford and then the steering angle data were scaled to simulate that trajectory in HVE. As these two types of data were available in the EDR the estimation of the trajectory became possible by using their combined results.

7. VEHICLE OCCUPANT'S RESPONSE TO THE IMPACT

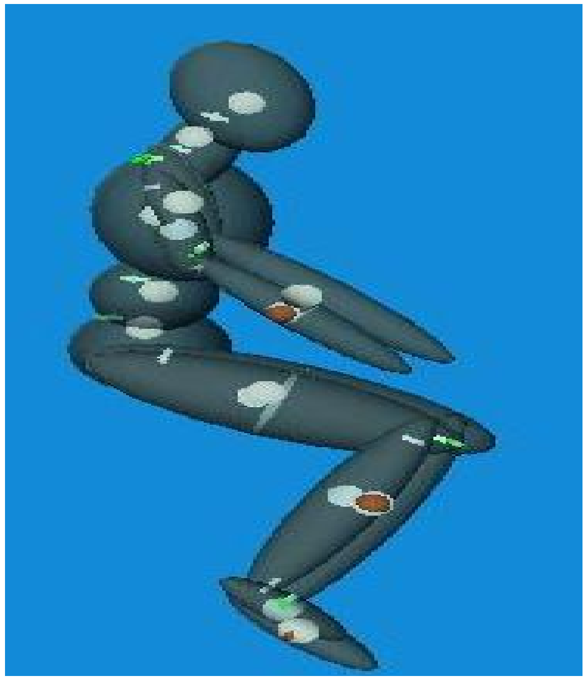
All accidents discussed so far were vehicle-to-vehicle collisions. Human interaction was not discussed. This chapter introduces the simulation of the vehicle occupant's response to the impact using the EDHIS simulation model in HVE. The collision pulse obtained from the simulation of the intersection accident is used as the input for this simulation. The response of the occupant for the restrained and unrestrained conditions is demonstrated qualitatively.

7.1 Accident Scenario

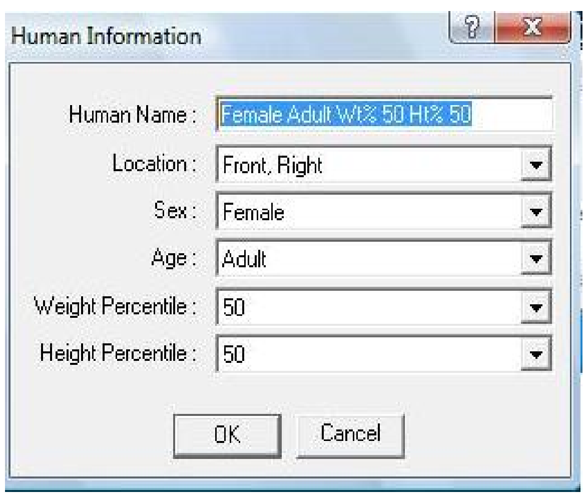
In the intersection accident discussed in Chapter 6, the Ford Escape's passenger side door popped open, and the female occupant was thrown out of the car because she was not wearing a seat belt.

7.2 Occupant Model for Simulation

As mentioned in Chapter 2, "Simulation Software: HVE Overview " one of the input editors in HVE is the human editor. This HVE human editor is used to design vehicle occupants' and pedestrians' models in 3D. The characteristics for these models are age, sex, weight percentile and height percentile. Figures 7.1(a) and 7.1(b) show the geometry and characteristics of the female adult chosen for this simulation.



(a) Female Adult



(b) Characteristics of the female adult

Fig. 7.1. Geometry and characteristics of a female adult

7.3 Collision Pulse from the Accident

As shown in Fig. 7.2, a collision pulse is the graph of vehicle acceleration versus time during impact. Therefore the collision pulse is a graphical representation of vehicle's response to the impact. This pulse was generated in EDHIS by first executing the accident in the EDSMAC4 simulation model which is the vehicle-to-vehicle impact simulation model discussed earlier. EDHIS also allows a user to import a collision pulse from the previously executed events in any HVE simulation model which removes the necessity of knowing vehicle dynamics.

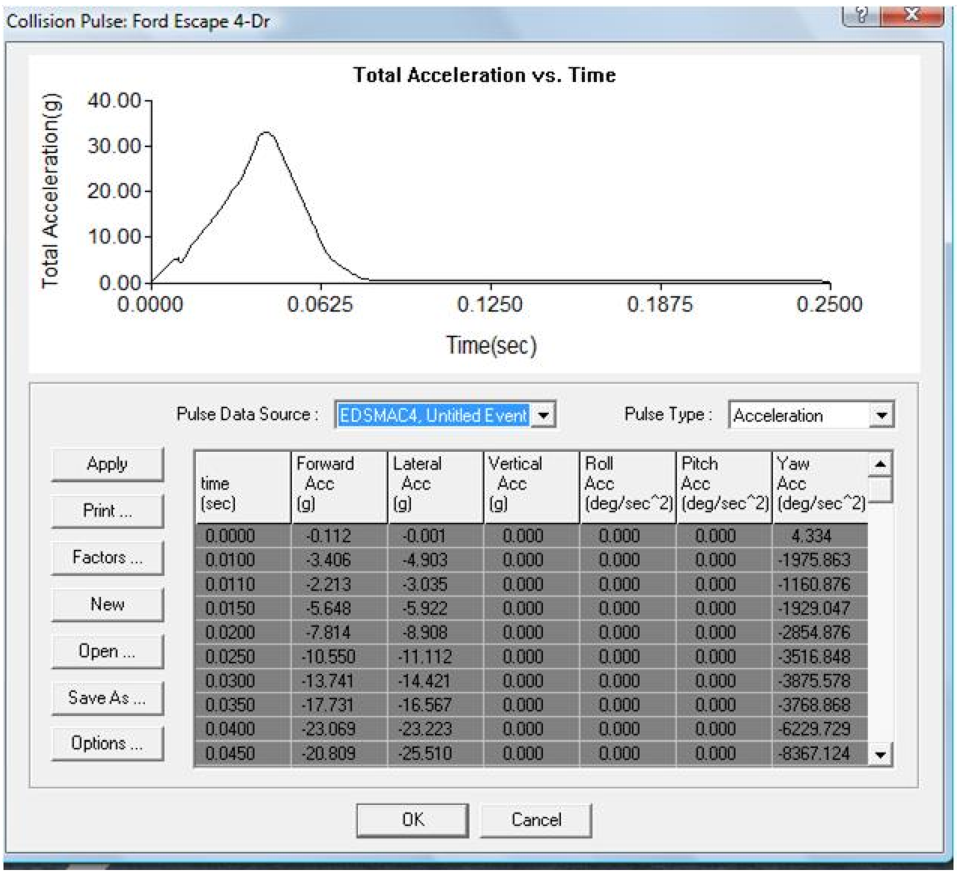


Fig. 7.2. Collision pulse

7.4 Contact Surfaces in a Car for an Occupant and a Car with No Top

The car without a passenger door needed to be modeled. The available geometry-profile of a car without roof and doors was chosen to serve that purpose. This is shown in Fig. 7.3

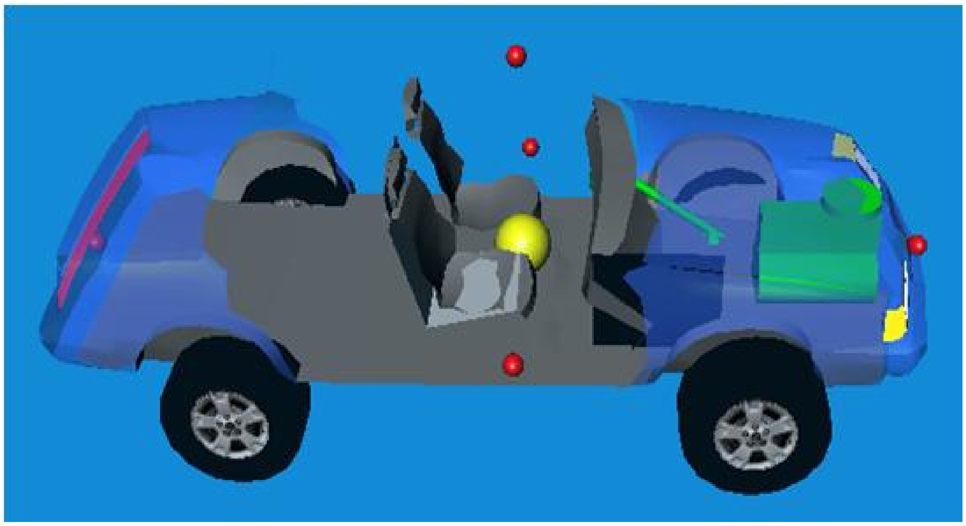


Fig. 7.3. Inner contact surfaces for the occupant

Contacts between a vehicle and a human ellipsoid do not exist by default in EDHIS. Contact surfaces need to be defined by entering the proper co-ordinates for vehicle surfaces which are coming in contact with a human. For the occupant's behavior, inner contacts such as the contact of a human with a vehicle's seat are generated. For a pedestrian accident, outer contacts such as contacts with a hood and wind shield are generated. Vehicle-contact surfaces generate contact forces on a human by interacting with a human ellipsoid. Fig. 7.4 shows an example of generated, seat-contact surfaces.

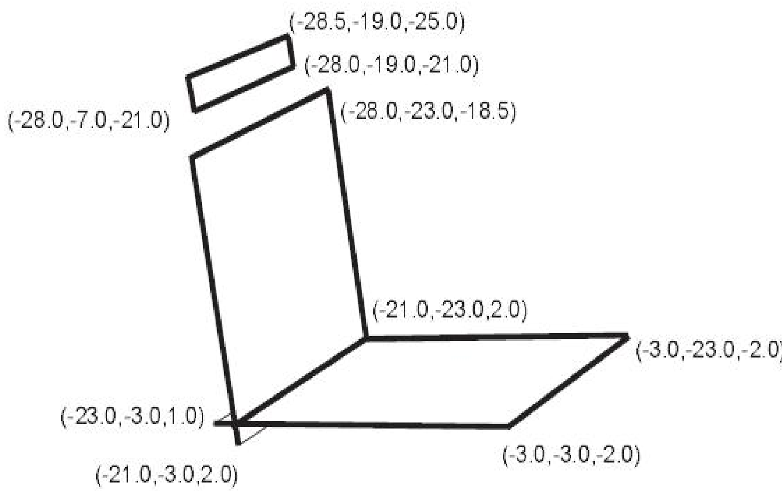
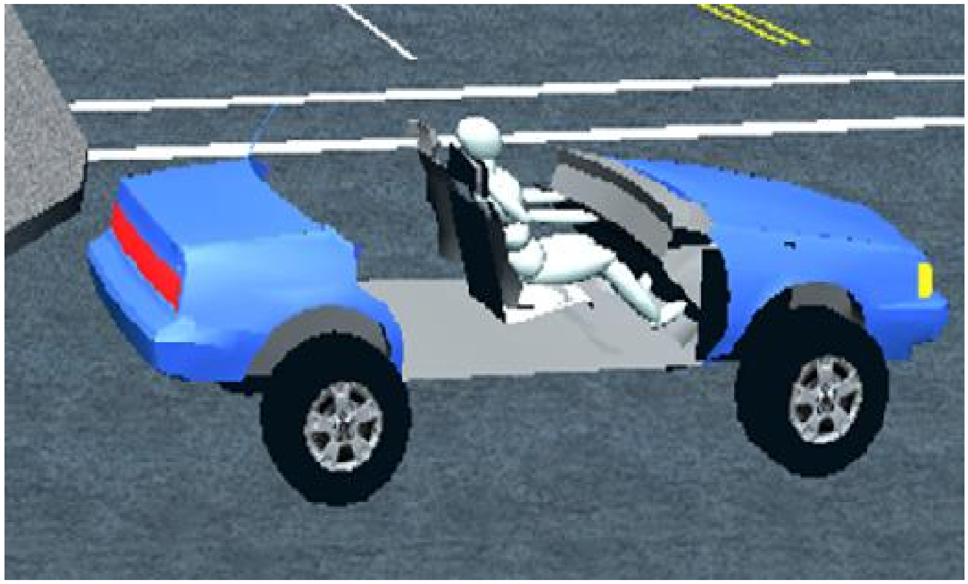


Fig. 7.4. Seat contact surfaces

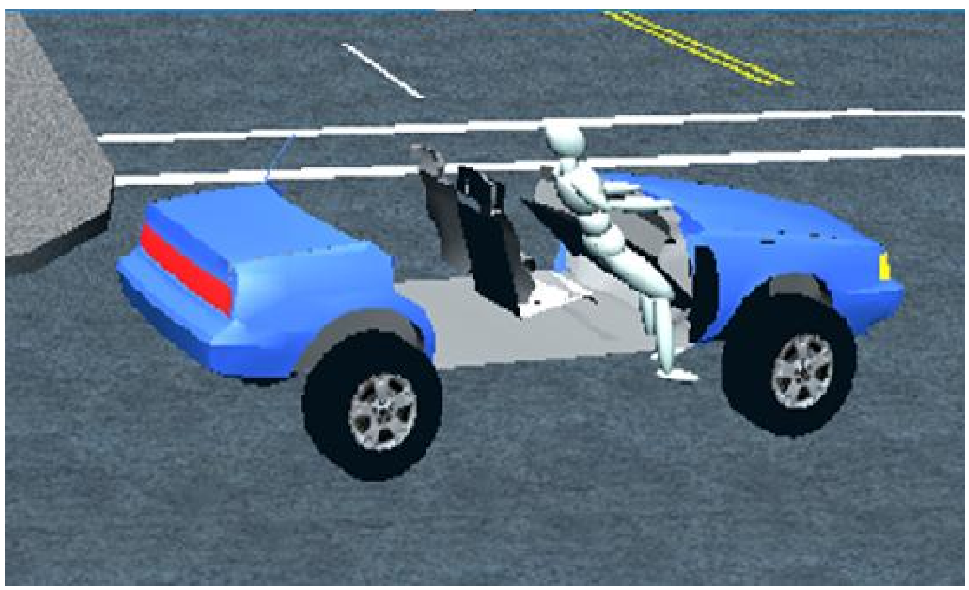
7.5 Simulation

The qualitative analysis was performed to observe the response of the occupant under restrained and unrestrained conditions. The following sections demonstrate these responses.

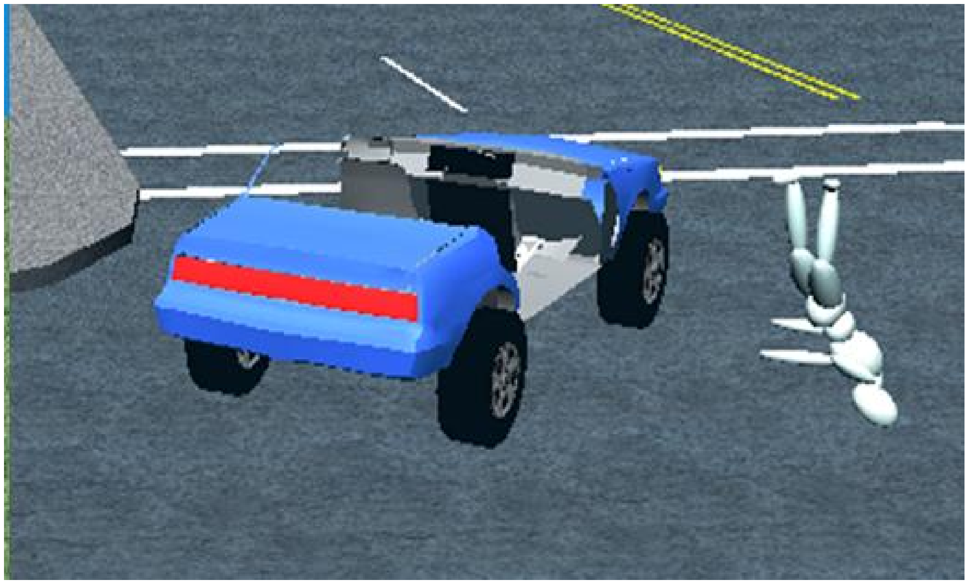
Unrestrained Occupant Figures from 7.5 (a) to (d) show the sequential simulation of the occupant's behavior for the collision pulse without the seat-belt restraint. When the simulation starts the car moves depending on its collision pulse parameters. As the vehicle dynamics at impact are represented by the collision pulse the oncoming car is not required to be present in the simulation. Based on the movement of the car and contact forces applied by the car's contact surfaces, the movement of the occupant is simulated. As shown in Figure 7.6(c), the unrestrained occupant lands on the ground which resembles the real-life scenario.



(a) The initial position of the occupant



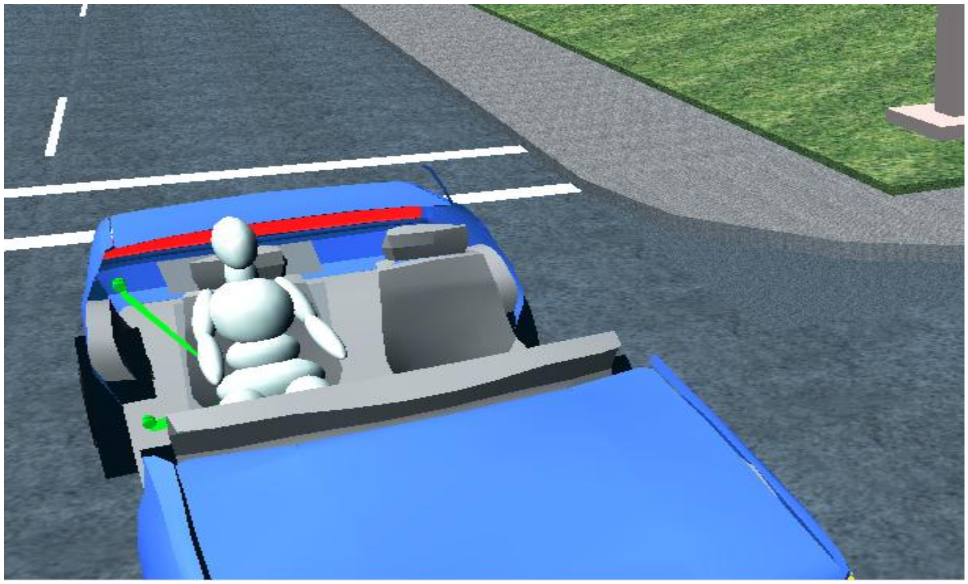
(b) The car receives the collision pulse and the occupant is being thrown from the car as he is not restrained by the seat belts



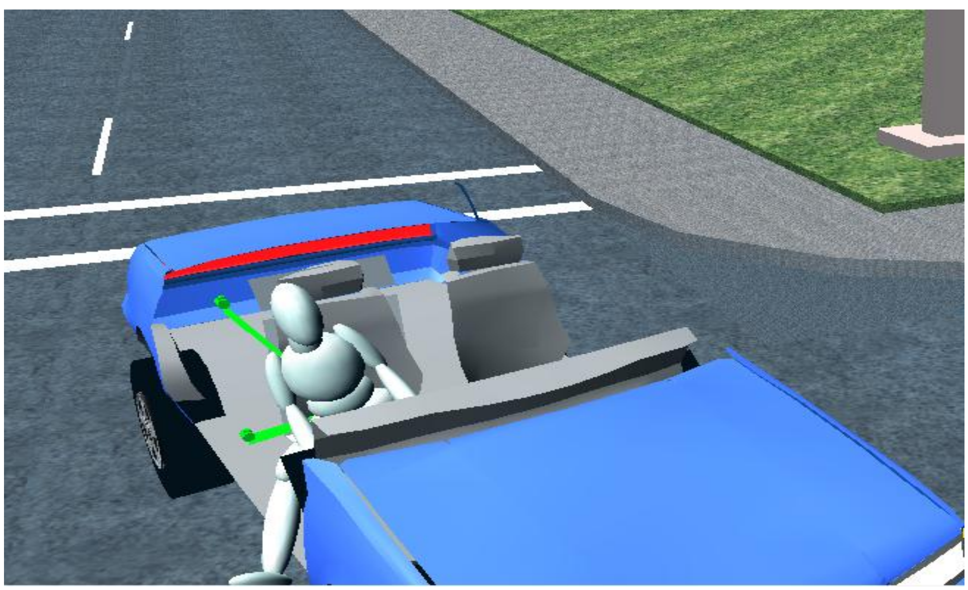
(c) The occupant lands on the ground

Fig. 7.5. The sequential simulation events for the occupant's behavior

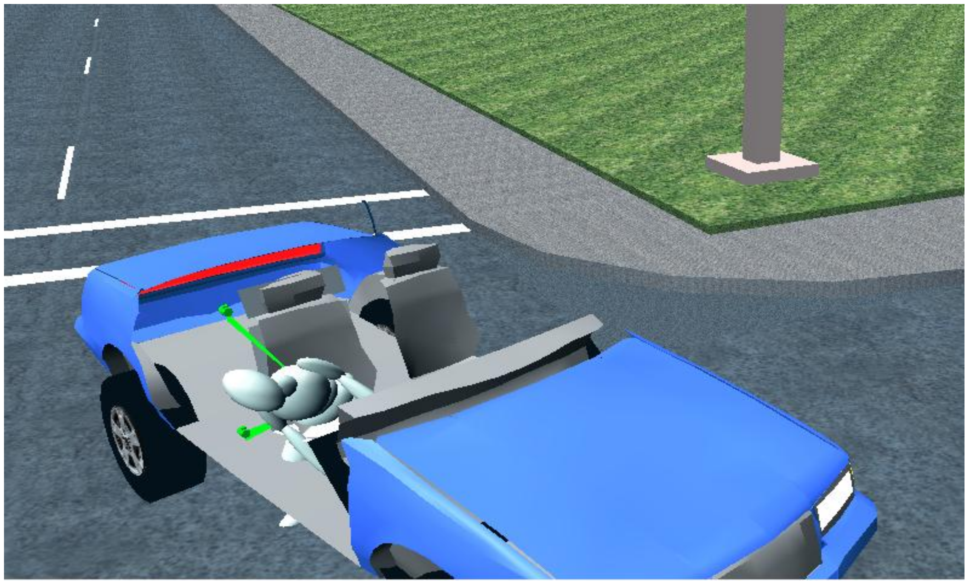
Restrained Occupant Figures from 7.6 (a) to (d) show the sequential simulation of the occupant's behavior for the same collision pulse with seat-belt restraints. Due to the restraints the occupant is not thrown out of the car.



(a) The initial position of the occupant having seat-belt status ON



(b) The car receives the collision pulse



(c) The occupant is restrained by the seat belt

Fig. 7.6. Sequential simulation for the occupant's behavior with seat-belt

7.6 Results of the Simulation

The EDHIS simulation method was used to simulate of the Ford occupant's response to the impact in unrestrained and restrained conditions. The results of the simulations were analyzed qualitatively. From these results it is clear that in the unrestrained condition the occupant fell on the ground because of the impact and sustained a severe head injury. While in restrained position the modeled occupant remained restrained to the car's seat and was not thrown out of the car.

7.7 Summary and Conclusion

The EDHIS method was used to study the occupant's response to the impact. The input used for that was the collision pulse obtained by executing the accident in the EDSMAC4 simulation method. The EDHIS method was an appropriate method for qualitative analysis of the occupant's response. No quantitative analysis was attempted.

8. CONCLUSION

In this thesis the simulations of three road-accident are presented using the HVE simulation software. The EDSMAC4 simulation method was used for the vehicle-to-vehicle collision simulation and EDHIS simulation method was used for occupant response simulation. Outputs were obtained from the simulations of three accidents and were compared to physical evidence and narrative reports. These outputs of the simulations were the rest positions of the vehicles (for position error calculation), damage profiles, tire-marks, and vehicle occupant's response for retrained and unrestrained conditions.

The bus-car accident was simulated by using conventional methods such as conservation of energy and momentum. The stiffness coefficient of the car was unknown. Also due to the large difference in the weights of the bus and the car, the initial velocity of the car could not be determined precisely. Had the pre-crash EDR data available for the car, those data would also have been helpful for determining the initial velocity, which in turn could have been useful to estimate its change in velocity. The three-vehicle accident and the intersection accident were simulated using the EDR data to estimate initial and impact velocities.

Some of the challenges in performing a simulation study were the limited information about vehicle dynamics, stiffness coefficients and the limited vehicle database available in HVE. For example, the actual model year of the Subaru involved in the bus-car accident was 2005, but this year was not available in the HVE database. So the model year range 1993-2001 was selected. Even if the laws of physics don't change over the years, the vehicle design changes rapidly and affects the accuracy of the simulation.

Actually the term "accuracy" might be a bit misleading when it comes to simulations of vehicle crashes. Usually the outputs expected from simulations are impact velocities, damage profiles, and vehicle trajectories. Given sufficient time, a programmer can adjust the input parameters in order to achieve the required output with minimum possible error. In this case, the accuracy of the simulation should be judged by the accuracy of the input parameters used [14]. For example, in the bus-car accident, a programmer may obtain the tire marks and rest position of the car as indicated on the AutoCAD surface, but be unable to match the impact velocity to within the prescribed tolerance. In this case the simulation results do not provide valid quantitative conclusions.

9. SUMMARY

Two simulation methods in HVE are used for simulation purpose in this thesis. The operation of HVE is based on laws of physics. While studying these accidents some limitations of the HVE software and its simulation methods were also observed. HVE is not an appropriate software to test environmental conditions such as rain and wind. In the HVE event-editor after setting up a particular event with selected vehicles more number of vehicles cannot be added. The EDSMAC4 simulation method terminates when tires of a vehicle lose contact with the road surface. Therefore, roll-over simulations cannot be performed using this method.

The three-vehicle accident and the intersection accident were simulated using the EDR data associated with each vehicle involved in those accidents. These data helped to obtain initial and impact velocities and the trajectory of the car in case of the intersection accident. The EDRs in the Electronic Control Modules in heavy duty vehicles record drivers' activities over a few recent consecutive months, which help in assessing their typical driving abilities. Most of the times EDR data can be helpful to find out the consistency between the driver's testimony and the recorded data. This helps decide whether the driver was at fault or not. For example, in the intersection accident the EDR-recorded initial speed of the oncoming Dodge was 45 mph in the speed zone of 35 mph. So the driver of the Dodge was also at fault even though it had the right of way. The EDR is useful to find out approximate initial speeds and impact speeds of vehicles which are necessary to estimate a crash severity which is useful in vehicle design. The EDR also records information such as airbag deployment, seat-belt status, and occupant size classification (adult/child). This information is useful to study the occupant's behavior. The EDR gets the information about the speeds of vehicles from sensors located at the tires. In accidents such as tire blow out and/or vehicle roll over the EDR may record wrong data. Therefore EDR data can be a supplementary tool in an accident reconstruction process, but it is not always a substitute for conventional accident-reconstruction methods.

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APPENDIX

APPENDIX : COMMERCIAL VEHICLE EDR DATA

DDEC® Reports - Monthly Activity #2

Print Date: Nov 02, 2004 12:41 PM (CST)

Truck City of Gary		Month:	October, 2004 (EST)
7360 W. Chicago Ave.		Vehicle ID:	13955
Gary, In 46406		Driver ID:	
1-800-552-4420		Odometer:	615907.1 mi

Distance	14308.1 mi	Time	314:37:11
Fuel	2002.88 gal	Fuel Consumption	6.37 gal/h
Fuel Economy	7.14 mpg	Idle Time	48:59:09
Avg Drive Load	47 %	Idle Percent	15.57 %
Avg Vehicle Speed	53.9 mph	Idle Fuel	16.00 gal

Driving Time	265:38:02
Driving Percent	84.43 %
Driving Fuel	1986.88 gal
Driving Economy	7.20 mpg
Vehicle Speed Limiting	
Time	54:56:14
Percent	20.68 %
Distance	3439.2 mi
Fuel	346.75 gal
Top Gear	
Time	214:23:35
Percent	80.71 %
Distance	13037.6 mi
Fuel	1738.75 gal
Top Gear - 1	
Time	15:13:00
Percent	5.73 %
Distance	643.4 mi
Fuel	116.38 gal
Cruise	
Time	117:42:43
Percent	44.31 %
Distance	7239.7 mi
Fuel	1030.63 gal
Top Gear Cruise	
Time	117:16:41
Percent	44.15 %
Distance	7219.7 mi
Fuel	1023.88 gal
Speeding A(>=66 mph and <71 mph)	
Count	935
Time	4:39:33
Percent	1.75 %
Speeding B(>=71 mph)	
Count	162
Time	0:45:32
Percent	0.29 %
Highest Speed	81.0 mph
Occurred	10/12/04 15:01:57 (EST)

VSG(PTO) Time	0:00:00
VSG(PTO) Percent	0.00 %
VSG(PTO) Fuel	0.00 gal
Stop Idle Time	30:14:08
Stop Idle Percent	9.61 %
Stop Idle Fuel	8.13 gal
Over Rev Limit	1800 rpm
Count	2573
Time	2:48:40
Percent	0.89 %
Highest RPM	2660 rpm
Occurred	10/14/04 01:14:39 (EST)
Diag. Records	14
Hard Brake Count	6
Brake Count	7371
Eng. Brake Time	0:00:00
Optimized Idle Time	
Active	0:00:00
Run	0:00:00
Battery	0:00:00
Engine Temp.	0:00:00
Thermostat	0:00:00
Extended Idle	0:00:00
Continuous	0:00:00
Fan On Time	
Total Time	19:35:26
Engine System	3:22:57
Manual	0:00:00
A/C	16:12:29
Pump On Time	
Time	0:00:00
Distance	0.0 mi
Fuel	0.00 gal
Coasting Time	0:01:43
Coasting Percent	0.01 %
Engine Utilization	42.23 %
Vehicle Utilization	35.66 %

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Fig. A.1. Sample EDR monthly activity report

DDEC® Reports - Trip Activity

Print Date: Nov 02, 2004 12:41 PM (CST)

Truck City of Gary
7360 W. Chicago Ave.
Gary, In 46406
1-800-552-4420

Trip: 02/28/2004 to 11/02/2004 (EST)
Vehicle ID: 13955
Driver ID:
Odometer: 615907.1 mi

Trip Distance	126246.3 mi
Trip Fuel	18090.50 gal
Fuel Economy	6.98 mpg
Avg Drive Load	49 %
Avg Vehicle Speed	54.6 mph

Trip Time	2717:05:09
Fuel Consumption	6.66 gal/h
Idle Time	405:45:16
Idle Percent	14.93 %
Idle Fuel	142.00 gal

Driving Time	2311:19:53
Driving Percent	85.07 %
Driving Fuel	17948.50 gal
Driving Economy	7.03 mpg
Vehicle Speed Limiting	
Time	501:02:17
Percent	21.68 %
Distance	31227.5 mi
Fuel	3607.13 gal
Top Gear	
Time	1909:56:55
Percent	82.63 %
Distance	116149.4 mi
Fuel	15912.88 gal
Top Gear - 1	
Time	114:46:04
Percent	4.97 %
Distance	4987.4 mi
Fuel	961.63 gal
Cruise	
Time	1052:01:02
Percent	45.52 %
Distance	64677.8 mi
Fuel	9240.25 gal
Top Gear Cruise	
Time	1048:13:25
Percent	45.35 %
Distance	64503.3 mi
Fuel	9186.88 gal
Speeding A(>=66 mph and <71 mph)	
Count	4714
Time	22:28:48
Percent	0.97 %
Speeding B(>=71 mph)	
Count	755
Time	4:19:29
Percent	0.19 %
Highest Speed	83.5 mph
Occurred	05/06/04 13:24:03 (EST)

VSG(PTO) Time	0:00:00
VSG(PTO) Percent	0.00 %
VSG(PTO) Fuel	0.00 gal
Stop Idle Time	245:36:31
Stop Idle Percent	9.04 %
Stop Idle Fuel	73.75 gal
Over Rev Limit	1800 rpm
Count	21768
Time	25:16:12
Percent	0.93 %
Highest RPM	2660 rpm
Occurred	10/14/04 01:14:39 (EST)
Diag. Records	180
Hard Brake Count	48
Brake Count	55993
Eng. Brake Time	0:00:00
Optimized Idle Time	
Active	0:00:00
Run	0:00:00
Battery	0:00:00
Engine Temp.	0:00:00
Thermostat	0:00:00
Extended Idle	0:00:00
Continuous	0:00:00
Fan On Time	
Total Time	229:36:51
Engine System	48:29:31
Manual	0:00:00
A/C	181:07:20
Pump On Time	
Time	0:00:00
Distance	0.0 mi
Fuel	0.00 gal
Coasting Time	2:21:52
Coasting Percent	0.10 %
Engine Utilization	45.65 %
Vehicle Utilization	38.83 %

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Fig. A.2. Sample EDR trip activity report

DDEC® Reports - Diagnostic Record #2

Print Date: Nov 02, 2004 12:41 PM (CST)

Truck City of Gary
7360 W. Chicago Ave.
Gary, In 46406
1-800-552-4420

Trip: 02/28/2004 to 11/02/2004 (EST)
Vehicle ID: 13955
Driver ID:
Odometer: 615907.1 mi

Diagnostic Code: **[84] - Oil Level Low**
Diagnostic Time: 10/30/2004 17:52:26 (EST)

Time	Vehicle Speed (mph)	Engine Speed (rpm)	Boost Press (psi)	Oil Press (psi)	Fuel Press (psi)
17:52:26	0.0	0	0.0	0.8	0.0
17:52:21	0.0	0	0.0	0.8	0.0
17:52:16	0.0	0	0.0	0.8	0.0
17:52:11	0.0	0	0.0	0.8	0.0
17:52:06	0.0	0	0.0	0.8	0.0
17:52:01	0.0	0	0.0	0.8	0.0
17:51:56	0.0	0	0.0	0.8	0.0
17:51:51	0.0	0	0.0	0.8	0.0
17:51:46	0.0	0	0.0	0.8	0.0
17:51:41	0.0	0	0.0	0.8	0.0
17:51:36	0.0	0	0.0	0.8	0.0
17:51:31	0.0	0	0.0	0.8	0.0

Time	Coolant Temp (°F)	Oil Temp (°F)	Fuel Temp (°F)	Engine Load (%)	Throttle (%)
17:52:26	78.5	59.8	93.5	0.0	0.0
17:52:21	78.5	59.8	93.5	0.0	0.0
17:52:16	78.5	59.8	93.5	0.0	0.0
17:52:11	78.5	59.8	93.5	0.0	0.0
17:52:06	78.5	59.8	93.5	0.0	0.0
17:52:01	78.5	59.8	93.5	0.0	0.0
17:51:56	78.5	59.8	93.5	0.0	0.0
17:51:51	78.5	59.8	93.5	0.0	0.0
17:51:46	78.5	59.8	93.5	0.0	0.0
17:51:41	78.5	59.8	93.5	0.0	0.0
17:51:36	78.5	59.8	93.5	0.0	0.0
17:51:31	78.5	59.8	93.5	0.0	0.0

Time	Engine Brake (cylinders)	Cruise	Accel Switch	Brake Switch	Clutch Switch
17:52:26	Off	No	No	No	No
17:52:21	Off	No	No	No	No
17:52:16	Off	No	No	No	No
17:52:11	Off	No	No	No	No
17:52:06	Off	No	No	No	No
17:52:01	Off	No	No	No	No
17:51:56	Off	No	No	No	No
17:51:51	Off	No	No	No	No
17:51:46	Off	No	No	No	No
17:51:41	Off	No	No	No	No
17:51:36	Off	No	No	No	No
17:51:31	Off	No	No	No	No

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Fig. A.3. Sample EDR diagnostics records report

DDEC® Reports - Daily Engine Usage

Print Date: Nov 02, 2004 12:41 PM (CST)

Truck City of Gary
7360 W. Chicago Ave.
Gary, In 46406
1-800-552-4420

Date Range: 10/30/2004 to 10/01/2004 (EST)
Vehicle ID: 13955
Driver ID:

Date:	10/27/2004
Start Time:	00:00:00 (EST)
Odometer:	614149.1 mi
Distance:	631.2 mi
Fuel:	87.50 gal
Fuel Economy:	7.21 mpg
Average Speed:	43.9 mph

Total(hh:mm)	14:22	03:10	06:28
Hour (EST)	Drive(min)	Idle(min)	Off(min)
00:00-02:00	114	6	0
02:00-04:00	71	14	35
04:00-06:00	76	32	12
06:00-08:00	61	17	42
08:00-10:00	56	16	48
10:00-12:00	42	8	70
12:00-14:00	65	23	32
14:00-16:00	34	11	75
16:00-18:00	66	10	44
18:00-20:00	118	2	0
20:00-22:00	98	16	6
22:00-24:00	61	35	24

Date:	10/26/2004
Start Time:	00:00:00 (EST)
Odometer:	613287.6 mi
Distance:	861.6 mi
Fuel:	123.75 gal
Fuel Economy:	6.96 mpg
Average Speed:	56.5 mph

Total(hh:mm)	15:15	02:06	06:39
Hour (EST)	Drive(min)	Idle(min)	Off(min)
00:00-02:00	116	4	0
02:00-04:00	3	2	115
04:00-06:00	19	20	81
06:00-08:00	112	0	8
08:00-10:00	46	35	39
10:00-12:00	120	0	0
12:00-14:00	116	4	0
14:00-16:00	117	3	0
16:00-18:00	35	27	58
18:00-20:00	66	23	31
20:00-22:00	112	2	6
22:00-24:00	53	6	61

Date:	10/25/2004
Start Time:	03:36:38 (EST)
Odometer:	612786.9 mi
Distance:	500.7 mi
Fuel:	58.75 gal
Fuel Economy:	8.52 mpg
Average Speed:	57.6 mph

Total(hh:mm)	08:42	01:12	14:06
Hour (EST)	Drive(min)	Idle(min)	Off(min)
00:00-02:00	0	0	120
02:00-04:00	8	6	106
04:00-06:00	42	8	70
06:00-08:00	97	10	13
08:00-10:00	58	29	33
10:00-12:00	0	0	120
12:00-14:00	0	0	120
14:00-16:00	0	0	120
16:00-18:00	59	4	57
18:00-20:00	118	0	2
20:00-22:00	95	1	24
22:00-24:00	45	14	61

ISP Report - 0152
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Fig. A.4. Sample EDR daily engine usage report