VEHICLE DYNAMICS USING COMPUTER SIMULATIONS AND EVENT DATA RECORDERS

A Thesis

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Mariana Alvarado Nava

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Student: Mariana Alvarado Nava

I certify that this student has met the requirements for format contained in the University format manual, and that this thesis is suitable for shelving in the Library and credit is to be awarded for the thesis.

__________________________, Graduate Coordinator

Akihiko Kumagai

__________________________, Date

Department of Mechanical Engineering
The police crash investigation department requires an engineering study of a vehicle crash before presenting a case to the judicial system. Vehicle crash reconstruction simulations establish new scientific basis for the judiciary system. Computer models are used to reconstruct the vehicle performance, since the dynamic performance of a vehicle collision cannot be repeated in real time. Vehicle dynamics is the engineering study of a vehicle based on mechanics and physics. This thesis uses modern techniques in combination with the information of Event Data Recorders (EDR) to help the judiciary system identify the safety parameters and condition of vehicles. The research analysis mainly focuses on the performance of police vehicles.

The EDR is a device installed in the vehicle to record how the driver responds to a crash event. Since 2004 the event data recorders are mandatory in every vehicle. Also, the EDR is able to analyze the change in velocity of the vehicle at the time of the impact. The analysis of the change in velocity allows a base structure for computer simulation.
A 3-D computer solid model of a 2004 Ford Crown Victoria is developed using Solidwoks. Also, dynamic computer simulations are developed using Adams View. The solid models consist of a tire assembly, a suspension assembly and a vehicle structure. These are assembled to form a complete model of the vehicle. The main objective is to analyze the vehicle’s performance during tactile driving maneuverers. The second objective is to provide new alternative methods to demonstrate a crash reconstruction to the judicial system. This method will provide a simpler, faster, and more accurate analysis of a vehicle dynamics. Additionally, the outcome of these simulations will provide a theoretical basis for future vehicle design.

_______________________, Committee Chair
Prof. Dr. Jose J. Granda

_______________________
Date
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1. INTRODUCTION

A. Statement of Collaboration

The California Highway Patrol's (CHP) Collision Investigation Unit (CIU) is responsible for documenting evidence and investigating vehicle collision events. The CIU provides in-depth crash investigations and analysis of major accidents throughout the state of California. These investigations include the reconstruction of the crash event, as well as the factor that caused the crash.

The reconstruction of the event consists of three collision phases: pre-collision, collision and post collision. The main collision factors in a crash event are environmental, human and mechanical. The CIU’s objective is to determine the different factors that cause collisions, and to prevent similar collisions from recurring.

B. Purpose

The main objective is the analysis the performance of a vehicle while executing police maneuver using 3-D modeling techniques. In order to achieve the 3-D simulations, the CIU office provides a series of real time maneuvers as used in officers’ training. These maneuvers are reproduced in 3-D dynamic modeling simulation and verified with the date obtained by the CIU. This data will be also verified by existing EDR information obtained from the police vehicle. The first test, a CHP vehicle skid test, consists of a computer simulation using Adams View to determinate friction forces, velocities and acceleration acting on the vehicle while applying the breaks. For the second test, a CHP vehicle maneuvers over a curve using Adams View to determinate maximum velocity for a vehicle to approach the curve safety. The third test, a CHP vehicle maneuvers over the entire police
academy track using Adams View to determine velocity changes along the track. This simulation will provide a reliable source for future vehicle dynamics analysis.
2. BACKGROUND OF THE STUDY

A. Vehicle Dynamics Method

Vehicle dynamics analysis is a numerical and experimental tool used to study the behavior of a vehicle. The dynamic is linear when a non-extreme behavior occurs. The nonlinear behavior occurs when any of the vehicle tires start skidding; this action is called saturation. The driver’s actions must be taken into consideration such as rotation of steering wheel, application of the brakes and acceleration input. The road conditions such as slippery and disturbances play a critical role. These conditions affect the friction forces between the road and the tires. A simple vehicle can be explained based on a linear model. Yaw rate, vehicle slip angle, and velocity are the state variables. The drive’s input causes rotational and translational responses, which results in inertia forces acting on the tires (first-order forces). A more complex model could analyze the wheel kinematics, vehicle structure, and load transfer.

The mathematical terms (state space) of a vehicle dynamic system is formulated as shown in equation 1 [1].

\[
\begin{align*}
\dot{x} &= Ax + Du \\
y &= Cx + Du
\end{align*}
\]

Where, \(x\) denotes the state vector, \(u\) denotes the input and \(y\) denote the system output. A simple linear dynamic model helps to understand the vehicle behavior. However, a dynamic mathematical system is not sufficient to solve vehicle dynamic model. The manipulation of multivariable analysis, Laplace transformation, and differential equations are necessary for this application.
The tire of a vehicle is the primary contact between vehicle and road. This contact is directly related to the vehicle performance. The horizontal and vertical forces are transferred on the vehicle by the tires. These forces are created by steering, braking and road conditions. Other external forces act on the vehicle such as aerodynamic forces. However, the tire-road forces dominate the vehicle behavior. Therefore, the emphasis of this paper is on tire-road contact. The tire forces and moment schematic is shown in figure 2.1[1].

Figure 2.1 Force and moments on tires

The forces acting are brake forces \( (F_x) \), lateral force \( (F_y) \), and tire load \( (F_z) \). The moments acting are overturning moment \( (M_x) \), moment about the wheel axis \( (M_y) \), and self-aligning moment \( (M_z) \). The velocity of tires is longitudinal \( (V_x) \) and lateral \( (V_y) \).
The tire structure consists of different rubber compounds and a mixed cord multi-layer reinforcement (check composites). The tire pattern or tire profile helps the tire to distribute the water in a wet environment to maintain a good tire-road contact. A vehicle tire must fulfill performance requirements such as low energy dissipation, good wear resistance, and good road-tire adherence.

To determinate the normal force, $F_z$, acting on a moving vehicle, consider a vehicle moving on flat road as shown in figure 2.2[2].

Assuming that aerodynamic forces are neglected, the equations of motion read as follow, [2].

$$2F_{x1} + 2F_{x2} = m\dot{v}$$  \hspace{1cm} (2)

$$2F_{z1} + 2F_{z2} - mg = 0$$  \hspace{1cm} (3)

$$2F_{x1}a_1 - 2F_{x2}a_2 + 2(F_{x1} + F_{x2})h = 0$$  \hspace{1cm} (4)

$$l = a_1 + a_2$$  \hspace{1cm} (5)

Figure 2.2 Vehicle moving on a flat road
Where, $a_1$ is the distance of the vehicle center of mass, $C$, from the front axle. $a_2$ is the distance of the center of mass from the rear axle. $l$ is the wheel base length. $\dot{v}$ is the vehicle’s acceleration. $m$ is the mass of the vehicle. Solving equation 2 and 3[1],

$$2F_{z1}a_1 - 2F_{z2}a_2 + (m\dot{v})h = 0$$

(6)

The equation 3 and 6 can be resolve for the normal forces,

$$F_{z1} = \frac{1}{2}mg\frac{a_2}{l} - \frac{1}{2}mg\frac{h}{l}\dot{v}$$

(7)

$$F_{z2} = \frac{1}{2}mg\frac{a_1}{l} - \frac{1}{2}mg\frac{h}{l}\dot{v}$$

(8)

B. Components of Vehicle Crash

The driver is in control of the speed and direction of the vehicle. The vehicle is the connection between the driver and the road. The vehicle is in contact with the road by the tires. The change in velocities is produced by traction forces developed on the tires. Design figures, maintenance, and repair are great influences on the mechanical conditions of a vehicle. The shape and surfaces of the road influence the vehicle motion. A crash is originated by the driver’s improper recognition of the road such as curves, road directions, and road surface. The driver recognition is affected though environmental factors such as fog, sun glare, and weather [3].

C. Vehicle Accident Reconstruction Principles

Accident reconstruction is the scientific approach used to determine the circumstances associated with a collision. It is important to investigate a crash, especially if someone has been injured or a crime has been committed [3].
A general reconstruction scenario is created with evidence such as photographs of the crash, police reports, and the physical wreckage of the vehicles. The reconstruction process usually works backward from the final position of the vehicle. The focus of a crash reconstruction is to analyze the collision to determine the cause of the accident. The reconstruction is analyzed in three main phases: pre-collision, collision, and post-collision. This study is focused on the pre-collision phase. The law of conservation of energy and the law of conservation of momentum are the two main physical laws that guide the analysis as explained in section 2.A[3], [4].

Vehicle crash reconstruction is based on basic equations of motion. Kinematics is the engineering branch that deals with the objects motion. The four basic quantities that apply to car reconstruction are acceleration, distance, initial velocity and final velocity. Distance is a linear measure from some point to another. For crash circumstances, distance is measured about a fixed coordinate system, for example, from the point where the driver applied the brakes. Time is useful to determinate the vehicle distance traveled during the event. Velocity is the rate of change in distance with respect to time. On a crash event, initial velocity is the vehicle velocity before the breaks are applied. acceleration is the change in velocity with respect to time[5].

The accident evidence is used in recreating the event. The evaluation of a vehicle’s damage shows the vehicle direction and angle of the collision. The velocity of the vehicle is calculated by the deformation of the vehicle’s body and chases. Abrasion marks on road show the motion and the position of the vehicles. Each vehicle has a different speed during the collision. The forces involved in a crash modified the speed, direction, and rotation of the vehicle. Friction forces usually leave marks on the road surface. The thrust between the vehicles collapses the vehicle structure. This collapse depends on the amount of force and the strength of the vehicle's structure. Besides
generating the vehicle's change in speed, the thrust makes the vehicle rotate or spin. This rotation depends on the point of application[6].

The law of conservation of energy states energy can neither be created nor destroyed, but it can be converted into different forms. The kinetic energy of a vehicle becomes zero when it comes to a stop. Most of the energy is usually converted into heat though the friction between the brakes and the road; the remaining kinetic energy is transferred into the deformation of the vehicles[7].

Momentum is defined as the mass of a vehicle multiplied by the velocity of the vehicle. The law of conservation of momentum states that within an event domain, the amount of momentum remains constant; momentum is neither created nor destroyed but only changed through the action of forces as described by Newton's laws of motion[7].

The three basic laws of motion provide insight into effects of the forces acting on bodies in motion. Newton’s first law of motion, the law of inertia, states a particle originally at rest or moving in a straight line with a constant velocity will remain in this state provided the particle is not subjected to an unbalanced force. Newton’s second law of motion, the law of constant acceleration, states that the acceleration of a particle as produced by a net force is directly proportional to the magnitude of the net force and inversely proportional to the mass of the object. Newton’s third law of motion, the law of momentum, states the mutual forces of action and reaction between two particles are equal, opposite and collinear. The laws of conservation of energy, conservation momentum and Newton's laws of motion are used to analyze the three reconstruction phases to establish initial factors of the crash event[7].

Pre-collision is the vehicle moments and dynamics prior to a crash chain. During this phase, braking, steering and tire forces affect the motion of the vehicle. The pre-collision starts with the
pre-impact velocity and ends at the moment of vehicle impact. The focus of this research is to
reconstruct different pre-collision events to analysis the behavior of the vehicle before an impact.
The critical reason is the last failure before a crash event. The U.S Department of Transportation
shows that 94% of the crashes critical reason is assigned to the driver while the other 4% is between
vehicle failure and environmental components [4].

The driver failures are classified into recognition error such as driver inattention or internal and
external distractions, decision error such as driving too fast, false assumptions and illegal
maneuver, and driver’s error such as poor directional control. The relation between driver errors
and the highway features is necessary to identify for highway design improvements. The highway
features are curvature, sight distance, lane width, bridge width, intersections, and pavement surface.

An accident event on a highway is complex due to the interactions of physical road condition, the
driver, vehicle, traffic and environmental conditions. The highway curves are necessary elements
of all highways. However, studies indicate that highway curves are assigned as the highest accident
locations. Highway curves are the most complex feature of a highway. The sight distance must
provide length along the road for the drivers to maneuver the vehicle and avoid a collision. The
pavement surface is related to the effects on vehicle control[8].

The effect of the vehicle speed reflects on the number of accidents. A study made by Yale
University reflects the rigid enforcement of speed regulation reduces the number of accidents. The
severity of a crash is related to the velocity of the vehicle. The faster the vehicle goes, the higher
the damage it generates. Also, as the vehicle velocity is increased, it becomes more difficult to
maneuver. It is harder to overcome obstacles or avoid dangerous situation at high velocities. Future
studies could analyze the drive’s ability to manage the vehicle at different velocities.
A better understanding of the pre-crash scenarios influences the safety technology systems such as brake assist, stability control, and driver warning systems. Recent efforts from the vehicle companies to decrease the numbers of crashes are the inclusion pre-collision systems. These systems help the driver prevent an accident by providing assistance when it is needed. There are four modern pre-collision system features: forward collision warning, auto braking, lane departure warning, and blind spot detection.

The collision warning and braking systems use a forward-looking sensor to detect the location and dynamic of the vehicle and provide warnings to the driver. This improvement also includes driver alerts and automatic braking. The combination of these two prevention crash systems works in three phases. The first phase provides a warning to the driver, and it prepares the braking system for a complete stop. The second phase of prevention systems slows down or stops the vehicle to prevent an impact. The third phase of prevention systems autonomously brakes the car without warning[9].

The collision phase begins with the first vehicle to vehicle contact and ends when the vehicles separate or when the vehicles reach the same velocity. During this event, the vehicle and passengers’ dynamic and kinematics factors are analyzed. Included are restraint systems, crash influencing, occupant position, interior safety, and others.

Delta-V (Δv) is defined as the change in velocity over the duration of the vehicle crash event, and it is considered one of the best predictors of crash severity. The magnitude of consequences of a vehicle collision is defined as severity. Severity is characterized as a property and health damage. Based on the severity, collisions are classified as property damage, injury crash, and fatality crash. The velocity of the vehicle can be determined by the coefficient of friction and the distance translated by the vehicle. The determination of the velocity of a vehicle after the collision is similar
in that the stiffness coefficients are comparable to the coefficient of friction. The stiffness coefficients and the length of the deformation are used to determine the speed [10], [11].

The National Highway Traffic Safety Administration (NHTSA) estimates delta-V from detailed measurements of vehicle deformation using the WinSMASH crash reconstruction code. Previous research has shown that WinSMASH delta-V estimates underpredict true delta-V by 25% on average. One possible explanation for this error is inaccuracies in the stiffness values used in the deltaV reconstruction calculation. The accuracy of codes, such as WinSMASH, is dependent upon vehicle stiffness values computed from post-impact crush measurements in crash tests. Any error in these crush measurements will be reflected as inaccuracies in the stiffness coefficients, and ultimately as errors in WinSMASH delta-V estimates. This paper investigates the accuracy of post-impact crush measurements in 93 frontal New Car Assessment Program (NCAP) tests of model year 2005-2007 vehicles[12].

Vehicle collision happen in different situations; the event could be a collinear or an angled vehicle collision. Collinear are a head-on collision, rear-end collision and collisions with the angle of impact of less than 10 degrees. Angular collisions are T-bone collision and collision with greater than 10 degrees’ angle of impact[10].

The impulse of momentum method is characterized by the vehicle’s mass, stiffness and velocity needed to generated a permanent damage. In a collinear collision, the dynamic of vehicle is based on Newton’s second and third laws. In this method, the collision phase is divided into two events: compression and restitution. The compression evaluates the initial velocity changes to a common final velocity of the vehicles. This leads to the following equation 9 [13].

\[ m_1v_1 + m_2v_2 = u(m_1 + m_2) \] (9)
Where $v_1$ is the velocity of vehicle one, $v_2$ is the velocity of vehicle two, $m_1$ is the mass of vehicle one, $m_2$ is the mass of vehicle two and $u$ is the final velocity of the vehicles.

The restitution is the elastic properties of the crash event. The restitution coefficient is obtained by Newton’s kinematic for centric impacts as shown in the following equation 10 [13].

$$e = \frac{u_2-u_1}{v_1-v_2}$$  \hspace{1cm} (10)

Where $e$ is the restitution coefficient. Equation one and two are the base line for every collinear car reconstruction.

The Static Stability Factor (SSF) is maximum angle for a vehicle to start rolling over. SSF is assigned to every vehicle. Vehicles are more likely to roll over while moving, than standing on a slope. There are two types of rollover situations: the first one is when a vehicle is drifting sideways and the wheels contact an obstacle that generates a pivot point such as a curve. The second type is when a vehicle enters a circular curve a high speed. In both cases the forces of gravity cross though the center of mass. The effect of the vehicle suspension and tire dynamics is essential to reduce a rollover tendency. However, modern electric and mechanical stability control in vehicles reduce the likelihood of rollover. Vehicle manufacture companies are not required to share the rollover risk with the customers, even though some vehicles are more likely to roll over.

The post-collision phase begins when vehicles separate and ends when the vehicles reach a rest position. In this collision phase, data is collected and measured to obtain the crash information. It is very important to collect as many crash parameters information as possible to allow investigators to create a complete momentum analysis. The important collision data includes tire marks, drawings of the vehicles’ trajectories and final position of the vehicles.
The collection of the crash information includes the examination of the vehicles lights, to ensure the brake lights are working and if tread the head lights were in functioning correctly. The examination of the tire condition, pressure levels and surface condition, help to determinate the road conditions. The damaged areas of the vehicles are evaluated for contact damage and induced damage. Contact damage is the damage caused by the direct contact of the vehicles. Induced damage is the damage produced by no direct forces of the collision. Windshield damage helps the investigators to evaluate airbag deployment and biomechanics. Finally, the measure of the vehicle damage provides a scale of vehicle deformation. The crash orientation is based on the damage patterns of the vehicle. This information is manipulated on computer-aided design (CAD) software to create a prototype of the vehicles[6].

D. Event Data Recorders

Event Data Recorders (EDR) have been required on every automobile since 2004 by The National Highway Traffic Safety Administration. As a standard equipment, EDR provides an independent measurement of crash severity, which avoids many of the difficulties of crash reconstruction techniques. EDRs have been used by automobile companies to evaluate the performance of their vehicles. The EDR provides a shot of the entire crash event by collecting and analyzing the vehicle’s performance. The data of an EDR is extracted by connecting it to a computer. The data extracted includes vehicle speed before the impact, seat belt usage, air bag deployment, velocity change, brake application and others factor[14], [15].

The first vehicles to use EDRs, as a safety feature, were the heavy trucks and buses such as school buses in 2003. The National Academy of Sciences National Research reports more than 800 children were killed in 2003 during school transportation hours. Due to the amount of casualties in school bus crashes, the National Highway Traffic Safety Administration (NHTSA) and the National
Transportation Safety Board decided to analyze the crashes by using EDR devices. The Truck Manufacturers Association (TMA) commented the EDR technology provided a better understanding of the bus crashes, which led to safety requirements for truck and buses. The TMA also added that “Potential future safety benefits include: increasing the accuracy of accident reconstruction, improving injury mechanism detection, providing data to vehicle manufacturers for improved vehicle design, and focusing resources where they are most needed”[14].

Engineering studies from Chalmers University of Technology provide a list of the benefits highway safety has gained by the collection and analysis of EDR data. The first benefit, development of safety equipment. Information of the crash dynamics from the EDR allows design improvements based on real data. This crash information is used as a base for biomechanics simulations to allow a better understanding of injuries and thus the improvement of safety equipment. The second benefit, structural vehicle requirements, the data obtained by the EDR is the base of comparison between the real-world crashes and laboratory crash testing. The third benefit, rule-making and safety evaluation, the EDR data provided a severity curves to help predict new safety standards. The last benefit listed, road design and resigned strategies, the data collected from the pre- and post–crash allows the modification of roads and to improve the road design strategies[14].

In 2004, Sandhill Community College conducted a research project about the advantage and disadvantages of event data recorders. The disadvantages are the reduction of private privacy, vehicle warranty disputes and the creation of paranoia. However, the disadvantages are not comparable to the number of positive impacts on society. The manufacturers benefit by evaluating the systems and the vehicle design performance. The government benefits at three different levels: federal, state and local. On the federal level, the EDR information helps to revise the standards safety performance of a vehicle. On the state level information assists to manage road systems and
improve road design. On a local level, the information assists emergency medical services. Law enforcement uses the data to validate and determine crash causation and fraud, and insurance companies benefit by avoiding fraudulent claims[14].

Emerging new technologies are also an important step in the use of event data recorders. The current vehicle standards and protocols will be replaced by new wireless networks and open standard interfaces, which will allow creativity and reliability in collected information of the EDR.
3. CROWN VICTORIA POLICE INTERCEPTOR TEST

A. General Information

The highway patrol crash investigation department invited professor Granda and his students to observed and participate on a crash investigation training. On the training, police investigators learn how to take notes of the crash event, read skid marks and the learn the basic of vehicle performance. The test was executed on a Ford Crown Victoria as shown in the following figure 3.1

![Figure 3.1 Highway patrol vehicle test](image)

B. Evaluation Information

The police skid test consists of a CHP vehicle applying the brakes until come to a complete stop. The test objective is to calculate the drag factor between the tires and the road by measuring the skid marks on the floor and using the accelerometer information. The initial conditions of the vehicle were written down on a report sheet as shown in figure 3.2. The tire conditions were obtain as shown in figure 3.3
Figure 3.2 Vehicle initial conditions report sheet

Figure 3.3 Tire conditions check
C. Test Equipment

The vehicle was equipped with 2 accelerometers (g-Analyst and Vericom) to measure the vehicle’s acceleration, velocity and time every 0.1 seconds for 3 seconds. An accelerometer is an electromechanical device that measures acceleration forces. The accelerometer is mounted on the vehicle to measure the acceleration forces acting on the vehicle while is moving. Figure 3.4 shows the g-Analyst Accelerometer. While, figure 3.5 shows how the g-analyst is mounted on the vehicle.

Figure 3.4 G-Analyst accelerometer

Figure 3.5 G-Analyst vehicle mount
Figure 3.6 shows the Vericom mounted on the vehicle.

Figure 3.6 Vericom vehicle mount

Also the vehicle equipped with an event data recorder as shown in the following figure 3.7

Figure 3.7 EDR vehicle mount
D. Vehicle Specs

This section describes the capacities and properties of the Crown Victoria Police Interceptor. Figure 3.8 shows a side and front representation of the Crown Victoria. Tables 1 - 3 describe the dimensions and capacities of the vehicle [16].

![Figure 3.8 Ford Crown Victoria Police Interceptor 2004](image)

<table>
<thead>
<tr>
<th>TABLE 3.1</th>
<th>Crown Victoria Exterior</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exterior (in)</strong></td>
<td></td>
</tr>
<tr>
<td>Length (A)</td>
<td>212.0</td>
</tr>
<tr>
<td>Wheelbase (B)</td>
<td>114.6</td>
</tr>
<tr>
<td>Width (C)</td>
<td>78.3</td>
</tr>
<tr>
<td>Height (D)</td>
<td>58.3</td>
</tr>
<tr>
<td>Base curb weight (lbs)</td>
<td>4136</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 3.2</th>
<th>Crown Victoria Width</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Track Width</strong></td>
<td><strong>in</strong></td>
</tr>
<tr>
<td>Front</td>
<td>63.4</td>
</tr>
<tr>
<td>Rear</td>
<td>65.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 3.3</th>
<th>Crown Victoria Engine I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine – 4.6L V8</td>
<td></td>
</tr>
<tr>
<td>Horsepower (hp @ rpm)</td>
<td>250 @ 5,000</td>
</tr>
<tr>
<td>Torque (lb.-ft. @ rpm)</td>
<td>297 @ 4,000</td>
</tr>
<tr>
<td>Fuel capacity</td>
<td>19.0</td>
</tr>
</tbody>
</table>
E. Test Results

The total distance traveled after applying the brakes was 70ft (21.5m). The drag factor was calculated between 0.7 to 0.75 by the police crash investigation students.
4. SOLID MODELING OF CROWN VICTORIA USING SOLIDWORKS 2016

A. Solid Modeling of Crown Victoria Structure

The chapter shows the steps to build the solid modeling of Crown Victoria Police Automobile 2004.

The solid modeling of the Crown Victoria was developed using Solidwoks 2016. The following steps were used:

1) The dimensions of the Crown Victoria structure are specified in section 3.D. Using a picture of the Crown Victoria side as a reference, trace the contour of the vehicle as shown in figure 4.1.

![Figure 4.1 Crown Victoria contour](image)

2) Generate the solid using the extruded feature (Appendix A) of the contour of the vehicle though the mid plane for 77 inches as shown in figure 4.2.

3) Using a front picture of the Crown Victoria as reference, trace the front contour of the vehicle. Using the extruded cut tool (Appendix A) shape the vehicle contour though
the whole solid. Figure 4.3 shows the front contour extruded cut.

4) Using the extruded cut feature, create the windows of the vehicle. The final Crown Victoria model is shown on figure 4.4.
The solid model of the steering knuckle was developed using SolidWorks 2016 software based on a standard suspension system. The following steps were used:

1) Sketch the following figure 4.5. Generate the solid using the extruded feature for 1 inch.
2) Sketch a 6-inch circle. Generate the solid using the extruded feature for 0.5-inches. Also, sketch a 1.5-inch circle and using the extruded cut feature make a hole as shown in the figure 4.6.
3) Using the extruded boss and extruded cut features generate the two rectangular pieces to support the bolt joins. Steering knuckle final solid model is shown in figure 4.7.
Figure 4.5 Steering knuckle sketch 1

Figure 4.6 Steering knuckle sketch 2
C. Solid Modeling of the Upper Suspension Support Arm

The solid modeling of the upper suspension arm was developed using Solidworks 2016 software. The following steps were used:

1) Sketched the following figure 4.8. Generate the solid using the extruded feature for 2-inches.

2) Sketch a 0.75-inch circle. Generate a solid circle using the extruded feature for 1-inch as shown on figure 4.9.

3) Sketch a 1-inch circle. Generate a hole through the entire solid using the extruded cut features. The final solid modeling of the upper suspension support arm is shown on figure 4.10.
Figure 4.8 Upper suspension arm sketch 1

Figure 4.9 Upper suspension arm sketch 2
The solid modeling of the front lower suspension arm was developed using Solidworks 2016 software. The following steps were used:

1) Sketched the following figure 4.11. Generate the solid using the extruded feature for 2-inches.

2) Sketch the following lines. Using the extruded cut feature make the cuts as shown on figure 4.12.

3) Using the extruded cut and linear pattern features, generate 0.25-inch holes along the solid as shown on figure 4.13.

4) Using the extruded cut feature, generate two holes of 0.8-inches though the body as shown on figure 4.14
Figure 4.11 Front lower suspension arm sketch 1

Figure 4.12 Front lower suspension arm sketch 2
5) Sketched the following figure 4.15 and 4.16. Generate the cut using the extruded cut feature.

6) Using the extruded boss feature, create two 0.5-inch solid circles for 1-inch. on each side. The final solid modeling of the front lower suspension support arm is shown on figure 4.17.
E. Solid Modeling of Back Lower Suspension Support Arm

The solid modeling of the back lower suspension arm was develop using Solidwoks 2016 software. The following steps were used:

1) Follow 1 through 6 steps of front lower suspension support arm, session 4.D.
2) Using the extruded cut figure, cut the back part of the solid as shown on figure 4.17.

![Figure 4.17 Back lower suspension arm sketch 1](image)

3) The final solid modeling of the back lower suspension support arm is shown in the following figure 4.18.

![Figure 4.18 Final solid model of back lower suspension support arm](image)
F. Solid Modeling of Tire

The solid modeling of the tire was developed using Solidwoks 2016 software. The following steps were used:

1) Sketch using a rectangle of 8.858-inches wide and 5-inches height. Using the fillet feature, fillet the corners by 1.50 inches. Using the pattern feature, create a pattern of 4 circles of 0.20 inches of radius along the top line of the rectangle as shown on figure 4.19.

2) Generate the tire solid using the revolved boss feature (Appendix A) by 360 degrees from the origin as shown on figure 4.20.

3) The final solid modeling of the tire is shown on figure 4.21.
Figure 4.20 Tire sketch 2

Figure 4.21 Final model of the tire
G. Solid Modeling of Rim

The solid modeling of the rim was developed using Solidwoks 2016 software. The following steps were used:

1) Sketch of a 17-inch circle. Generate the rim solid using the extruded feature for 7-inches as shown on figure 4.22.

2) Sketch of another circle of 16-inches from the origin. Generate a cut using the extruded cut the circle for 3.5 inches as shown on figure 4.23.

3) Sketched a polynomial shape on the solid face of the rim. Applied a circular pattern with the pattern tool for 360 degrees. Using the extruded cut tool, cut though the solid model as shown on figure 4.24.

4) Sketched another circle of 4.50-inches from the origin. Using the extruded cut feature, cut solid for 2.5 inches as shown on figure 4.25.
Figure 4.23 Rim sketch 2

Figure 4.24 Rim sketch 3
5) Sketch 4 circles of 0.5-inches. Using the extruded cut feature, cut the circles through the solid. The final solid modeling of the rim is shown in the following figure 4.25.
H. Solid Modeling of the Hub

The solid modeling of the hub was develop using Solidwoks 2016 software. The following steps were used:

1) Sketched a 4.5-inches circle. Using the extruded boss feature, generate the solid for 6 inches as shown on figure 4.27.

2) Sketch 4 circles of 0.5-inches. Using the extruded boss feature, create the solid of the circles for 1.5 inches as shown on figure 4.28.

3) On the other side of the hub, sketch a circle of 1.5 inches. Using the extruded boss feature, generate the solid for 1.5 inches as shown on figure 4.29.

![Figure 4.27 Hub sketch 1](image)
At the end of the solid created in the last step, sketch a circle of 3.75 inches. Using the extruded boss feature, generate the solid for 1 inch. The final solid modeling of the hub is shown in the following figure 4.30.
I. Solid Modeling of Front Suspension Support Assembly

Due to software limitations the vehicle assembly needs to be as simple as possible, yet accurate, to export to Adams. Adams View software is explained in detail in chapter 5. This suspension support assembly is used on the 2 front tires of the Crown Victoria. The assembly model of the suspension support was developed using Solidwoks 2016 software. Using the mate tool (Appendix A), create the following mates:

1) Top steering knuckle hole and front upper support solid circle are concentric.
2) Front face of upper support and back rectangular face of the steering knuckle are coincident.
3) Bottom steering knuckle holes and lower support solid circles are concentric.
4) Outside face of lower support and inside face of steering knuckle are coincident.

The final assembly model of the front suspension support is shown in the following figure:
Due to software limitations the vehicle assembly needed to be as simple as possible, yet accurate, to export to Adams. This suspension support assembly is used for the 2 back tires of the Crown Victoria. The assembly model of the suspension support was developed using SolidWorks 2016 software. Using the mate tool (Appendix A), create the following mates:

1) Bottom steering knuckle holes and lower support solid circles are concentric.

2) Outside face of lower support and inside face of steering knuckle are coincident.

The final assembly model of the back-suspension support is shown in the following figure.
Due to software limitations the vehicle assembly needed to be as simple as possible, yet accurate, to export to Adams. All the rotating parts are included in one tire assembly. This assembly is used in the 4 tires. The solid modeling assembly of the tires was developed using Solidworks 2016. Using the mate tool (Appendix A), create the following mates:

1) Tire and rim circular geometry are concentric.
2) Tire front face and rim front face are coincident.
3) Rim and front hub circular geometry are concentric.
4) Rim back face and front hub front face are coincident.

The final solid modeling assembly of the tire is shown in the following figures.
Figure 4.33 Final front tire assembly solid modeling (front view)

Figure 4.34 Final front tire assembly solid modeling (back view)
L. Solid Modeling of the Crown Victoria Assembly

Due to software limitations the vehicle assembly needed to be as simple as possible, yet accurate, to export to Adams. The Crown Victoria assembly consists of the vehicle structure and 3 main sub-assemblies: front suspension support assembly, back suspension support assembly and tire assembly. The solid modeling assembly of the Crown Victoria was developed using Solidwoks 2016. Using the mate tool (Appendix A), create the following mates:

1) Using the mate tool, make the top of the suspensions coincident as well as parallel as shown in the figure 4.35

2) Using the mate tool, make the circle of the steering knuckle concentric with the vehicle structure as shown in the following figure 4.36.

3) Using the mate tool, make the tire assemblies and the suspension support assemblies concentric and coincident.

Figure 4.35 Front and back suspension support mates
The final solid mode assembly of the Crown Victoria is shown in the following figures:

Figure 4.36 Suspension supports and vehicle structure mates

Figure 4.37 Crown Victoria solid model side view
Figure 4.38 Crown Victoria solid modeling back view

Figure 4.39 Crown Victoria 3-D view
5. SOLID MODELING OF THE HIGHWAY PATROL ACADEMY TRACK USING SOLIDWORKS 2016

This chapter covers the road background and calculation, as well as the procedure to create a 3-D model of the police academy track using Solidworks.

A. Simple Horizontal Curve with Constant Radius

The performance of the vehicle is influenced by the roughness and friction properties of the road. A realistic road representation must provide the elevation of the road and the friction properties. Figure 5.1 shows an example of a road segment with x, y, and z profiles.

Figure 5.1 Road profile
Geometric design of highways deals with physical elements such as vertical and horizontal curves, lane widths and clearance. This study is focus on simple horizontal curves with a single constant radius. Figure 5.2 shows an example of a simple-curve with constant radius.

Where $R$ is the curve radius. $\Delta$ is the central angle of the curve. $PC$ is the initial point of the curve. $PI$ is the point of tangent intersection. $PT$ is the end point of the curve. $T$ is the tangent length. $M$ is the middle ordinate. $E$ is the external distance. $L$ is the length of the curve.

The equations for a simple horizontal curve are read as follow,

$$T = R \tan \frac{\Delta}{2}$$ \hspace{1cm} (11)

$$E = R \left[ \frac{1}{\cos^2 \frac{\Delta}{2}} - 1 \right]$$ \hspace{1cm} (12)

$$M = R \left[ 1 - \cos \frac{\Delta}{2} \right]$$ \hspace{1cm} (13)

$$L = \frac{\pi}{180} R \Delta$$ \hspace{1cm} (14)
B. Superelevation of Horizontal Curves

The superelevation or banking is an inclination of the road toward the center of the horizontal curve. The purpose of the superelevation is to avoid the vehicle to slide out of the curve due to centripetal acceleration acting on a vehicle while driving through the curve. Figure 5.3 shows a vehicle on a curve and the forces in contact.

Where \( R_v \) is the curve radius. \( \alpha \) is the angle of inclination. \( e \) is the number of vertical length of rise per 100 of the horizontal distance. \( W \) is the weight of the vehicle. \( F_f \) is the side friction force. \( F_c \) is the centripetal force. The superelevation equation read as follow,

\[
R = \frac{v^2}{g \left( f_s + \frac{e}{100} \right)} \quad (15)
\]

\[
\frac{e}{100} + f_s = \frac{v^2}{15R_v} \quad (16)
\]
C. California High Patrol Academy Track

The California High Patrol Academy teaches new police officers fundamental principles including criminal law, accident investigation, police vehicle operations, report writing and others. The CHP practice their maneuvers and teach collision investigations on the track. Figure 5.4 shows the Police Academy from a Google satellite view.

![Figure 5.4 California Highway Patrol Academy](image)

The Highway Patrol Academy track consists of 5 different curves and 5 straight lines. A diagram of the track is shown in figure 5.5, where C is curve and S is straight line. Each part was analyzed and created separately.
D. Solid Modeling of Highway Patrol Academy Track Straight Lines

The diagram shown on figure 5.5 serves as reference for the nomenclature of track sections. All the straight lines are created the same way in Solidworks, but with different extruded distance. The following figure 5.6 show the distance calculation for the straight line of the highway patrol academy track. The straight lines were calculated using Bluebeam Revu 2016. Where the measure tool was calibrated with the scale lines from google maps.
The solid model of the straight lines on the track were develop using Solidwoks 2016 software based on the information explained on the previous sections of this chapter. The following steps were used:

1) Sketch a rectangle of 50fts. long and 2fts. tall as shown in figure 5.7
2) Using the extruded boss (Appendix A), create the solid model with the specific distance shown in figure 5.6. Figure 5.8 shows an example.
E. Curves Radius Distance and Angle Calculators

The following figure 5.9 show the radius distance and angle calculation for the curves of the highway patrol academy track. The curves were calculated using Bluebeam Revu 2016. Where the measure tool was calibrated with the google scale lines.

Using the equations from sections 5.A and 5.B, the curve information is obtained as shown in the following table 5.1. The speed limit of the curve is an assumption to find the superelevation of the curve. Table 5.1

![Figure 5.9 Curves calculations](image-url)
Table 5.1
Curve Calculations Results

<table>
<thead>
<tr>
<th>Curve Number</th>
<th>Radius (ft)</th>
<th>Degrees of Amplitude (°)</th>
<th>Speed Limit (mph)</th>
<th>Superelevation Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>932</td>
<td>73.7</td>
<td>55</td>
<td>5.7</td>
</tr>
<tr>
<td>2</td>
<td>523</td>
<td>121.6</td>
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<td>5.7</td>
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<td>3</td>
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<td>5</td>
<td>196</td>
<td>134.7</td>
<td>30</td>
<td>8.5</td>
</tr>
</tbody>
</table>

F. Solid Modeling of Curves

The solid models of curves were develop using Solidwoks 2016 software based on the information explained on the previous sections of this chapter and the information from table 5.1. The following steps were used:

1) On the top plane, sketch a profile of the curve such as the curve radius and the degrees of amplitude of the curve. Figure 5.10 shows as example sketch of the curve 1.

2) Create planes (Appendix A) at the ends and the center of the curve as shown in figure 5.11.

3) Sketch a rectangle profile at the end of the curve. The rectangle is 50 fts. long a 2 fts high as shown in figure 5.12.

4) On the center sketch the super elevation as shown on figure 5.13.

5) Create a 3-D sketch that connects the 3 profiles as shown in figure 5.14.

6) Create the curve solid model using the load boss feature (Appendix A). Using the 3 different 2-D sketches as profiles and using the 3-D sketch as Guide curves as shown in figure 5.15.
Figure 5.10 Curve sketch 1

Figure 5.11 Curve sketch 2
Figure 5.15 Curve lofted boss

The final solid model of the curve is shown in figure 5.16

Figure 5.16 Final solid model of curve 1
G. Highway Patrol Academy Track Assembly

Due to software limitations the track assembly needed to be a simple as possible, yet accurate, to export to Adams. The solid modeling assembly of the Highway Patrol Academy track was developed using Solidwoks 2016. Using the mate tool (Appendix A), create the following mates:

1) Create a coincident mate at the edges (top and side) of each curve geometry, as shown on figure 5.17

The final solid mode assembly of the Highway Patrol Academy track is shown in the following figures:
Figure 5.18 Side view of the Highway Patrol Academy Track

Figure 5.19 Top view of the Highway Patrol Academy Track
6. ADAMS DYNAMIC SIMULATIONS

A. Solid Model Transfer from Solidwoks to Adams View

The solid modeling of the Crown Victoria was developed using Solidwoks 2016; the modeling steps are explained in detail in chapter 4. To transfer a solid model from Solidwoks to Adams View, the study motion tab on Solidworks window is used. Under the study motion tap, choose the motion analysis simulation option. After running the simulation, right click on the project and select the export to Adams option. The only problem using Solidwoks – Adams transfer, the constrains work different for each software. The Crown Victoria model appears as shown in figure 6.1. Some modifications are needed to avoid errors in Adams. The top bar of the window is the tool bar. The left bar is the model tree.

Figure 6.1 Adams setup
B. Crown Victoria Adams Assembly

This section 6.B needs to be repeated on any Adams simulation to assemble the vehicle properly. The properties of the model need to be modified to obtain the needed results. It is recommended to change the appearance and the name of the parts to simplify navigation. Using the body modify dialog box, modify the mechanical properties of the vehicle as specified in chapter 3, section D, as shown in figure 6.2. Delete all the connectors transferred from Solidworks. Assemble the tires and the suspension supports by using a Hooke joint, located at the connectors tab on the tool bar. Use the center of the tire and the steering knuckle as reference for the joint. The assemble of a tire-suspension is shown in the following figure 6.3.

![Figure 6.2 Vehicle mechanical properties in Adams](image-url)
On the force tab, create gravity force as shown in figure 6.4. On the same tab, create contacts between the suspension and the tire assembly as shown in figure 6.5. Also, create contacts between the tires and the ground as shown in figure 6.6.
Figure 6.5 Tire-suspension contact

Figure 6.6 Tire-road contact
C. Skid Test

The skid test consists of a CHP vehicle applying the brakes until come to a complete stop. The test objective is to calculate the drag factor between the tires and the road. On the CHP real time skid test, the vehicle was equipped with 2 accelerometers to measure the vehicle’s acceleration, velocity and time every 0.1 seconds for 3 seconds. The total distance traveled after applying the brakes was 70ft. The drag factor was calculated between 0.7 to 0.75.

The 3-D vehicle dynamics simulation are created to verify the calculation and the vehicle performance of the CHP vehicle. Adams view was used to determinate the velocities and forces acting on the vehicle, as well as the distance travel and drag coefficient. The 3-D simulation consist of a Crown Victoria Vehicle with an initial velocity of 40 mph that reaches stop by applying the breaks. Using the mechanical properties of the vehicle as shown in section 3.E and drag factor of .75. Chapter 5 explains the procedures used to create a Solidworks model of the ford Crown Victoria 2004. After following the vehicle setup steps explained in section 6.B, create a translational joint between each tires are the ground as shown in figure 6.7 to lock in the tires. Create a friction join by modifying the translational join, click on the friction join figure as shown in figure 6.8.

Apply an initial velocity to the vehicle by modifying the vehicle. Using the category pull down bar, select velocity initial condition. Create a 40mph velocity on the Z axis as shown in figure 6.9.
Figure 6.7 Translation joint

Figure 6.8 Friction setup
The results of the 3-D simulation are shown in the following figures 6.10 to 6.12. Force acting on the front tires reaches 2741.54 lbf. The force acting on the back tires reaches 1083.354 lbf. This means that the drag factor is different for the front and the back tires.
The results from the 3-D simulation are fairly close from the CHP results. Figure 5.13 shows the travel distance of the vehicle as 70.53ft. Figure 5.14 shows the velocity of the vehicle, where the vehicle takes 2.3 seconds to reach the stop. Figure 5.15 shows the acceleration of the vehicle. These results are very close from the real-time values into 0.7% difference. The difference with the results
could be assigned to the tire and road conditions. A video of the performance is included with the thesis documentation.

Figure 6.13 Vehicle travel distance

Figure 6.14 Velocity of the vehicle

Figure 6.15 Vehicle acceleration
On the acceleration graph is possible to observe the change in acceleration at before the vehicle stops. This change in acceleration could cause injuries to the passenger.

D. Vehicle Performance Over a Curve

The curve test consists of a CHP vehicle taking over a curve. The objective of the simulation is to analyze the stability of the vehicle while approaching the curve. Chapter 5 explains the procedure used to create the Crown Victoria Solidworks model. Chapter 5 explains the procedure used to create the highway curve. This curve has a radius of 983 ft. It is designed to have a 55 pmh speed limit. The curve maximum elevation has an angle of 5.7 degrees. After following the vehicle Adams setup steps from section 6.B, create spline to give the vehicle direction as shown in Figure 6.16. Create a point-curve constraint between the vehicle and the spline as shown in figure 6.17. This constraint does not affect the vehicle preference or forces the vehicle over a path.

Figure 6.16 Spline path
Create a constant velocity for the vehicle by modifying the point – curve constrain as shown on figure 6.18.

The speed limit for this curves is 55mph as explain in chapter 5. The following figure 6.19 to 6.22 show the vehicle performance when the vehicle approaches the curve at 55mph.
Figure 6.19 Initial conditions for vehicle performance over a curve (55 mph)

Figure 6.20 Vehicle Performance over a curve after 2 sec (55 mph)
Figure 6.21 Vehicle performance at the end of the curve (55 mph)

Figure 6.22 Top view of vehicle performance over a curve (55 mph)
The following figures 6.23 to 6.28 show the velocity and acceleration of the vehicle. Also, the force acting on the tires, respectively.

Figure 6.23 Velocity of the vehicle over the curve in ft/s (55 mph)

Figure 6.24 Acceleration of the vehicle over the curve (55 mph)

Figure 6.25 Forces acting on the front right tire (55 mph)
Figure 6.26 Forces acting on the left front tire (55 mph)

Figure 6.27 Forces acting on the back right tire (55 mph)

Figure 6.28 Forces acting on the back left tire (55 mph)
The graphs show that the forces acting on the tires is different on each tires. The difference on the forces is due to the geometry of the road, where the road is on a superelevation on 5 degrees.

The vehicle starts losing stability when the tires are not perpendicular to the surface. When the vehicle is not stable, any disturbance on the road could cause the vehicle to start skidding and the driver could lose control of the vehicle. Figure 6.29 shows the tires at 55 mph. Figure 6.30 shows a representation when the tires are not stable.

Figure 6.29 Tires at 55mph

Figure 6.30 Tires at 100mph
At 100mph the tires are not tangential with the road. This inclination makes the vehicle be unstable and it could be easy to lose control. Figure 6.31 to 6.35 shows the forces acting on the tire when the vehicle speed is 100mph. Videos of the performance of the vehicle are part of this thesis.

![Figure 6.31 Velocity of the vehicle while taking the curve (100 mph)](image1)

![Figure 6.32 Forces acting on the front right tire (100 mph)](image2)
Figure 6.33 Forces acting on the front left tire (100 mph)

Figure 6.34 Forces acting on the back left tire (100 mph)

Figure 6.35 Forces acting on the back right tire (100 mph)
E. Vehicle Performance Over the Police Academy Track

The police academy track test consists of a CHP vehicle performing over the entire police academy track. The objective is to analyze the performance of the vehicle over different curves. Chapter 5 explains the procedure used to create the Crown Victoria Solidwoks model. Chapter 5 explains the procedure used to create the entire track. After following the vehicle Adams setup steps from section 6.B, create spline to give the vehicle direction as shown in Figure 6.36.
Create a point-curve constraint between the vehicle and the spline as shown in figure 6.37. This constraint does not affect the vehicle preference or forces the vehicle over a path.

Create a constant velocity for the vehicle (45 mph) by modifying the point – curve constrain as shown on figure 6.38.
After running the simulation is possible to observe the vehicle performance over the track. The initial velocity of the vehicle is 45mph. The vehicle starting moving from S2 until C1 for a 60sec period. The following figure 6.39 shows the velocity graph of the vehicle over the track.

Figure 6.39 Velocity graph of the vehicle over the track

Figure 6.40 shows the vehicle acceleration graph. The data obtain from Adams had to be transfer to Excel to show the proper units. By studying this graph, the simulation could be improved, the vehicle should not exited +1 g.

Figure 6.40 Acceleration graph of the vehicle over the track (g)
Figures 6.41 to 6.43 show the forces acting on each tire over the track obtained from Adams.
The following figure 6.45 shows the data obtained from the Powertrain Control Module (PCM) on the police vehicle. The graph shows the velocity of the vehicle over the Highway Patrol Academy track in miles per hours. Also, shows when the brakes were applied over a 126 seconds period. The following figure 6.46 shows the data obtained from the ACM. The graph shows the acceleration and the delta V of the vehicle while driving over the track over a 140 m-seconds period. Use appendix C for more information about event data record data and the Highway Patrol Academy track test.
The information obtained on the simulation is reliably similar to the real-time test. The velocity of the vehicle changes on both graphs when the vehicle is taking a curve in a similar profile. However, the real-time test had acceleration input from the driver. This simulation could be improved by simulating the break and acceleration of the vehicle. Also, the elevation of the road could be improved to obtain more accurate results.

Figure 6.46 ACM data of the vehicle velocity over the Highway Patrol Academy Track
7. CONCLUSION

The analysis describes the dynamics and control of the Ford Crown Victoria police vehicle during the police maneuvers. The influences of the drag factor and the forces acting on the tires, as well as the position, velocity and acceleration of the vehicle has been investigated on the skid test. The stability of the vehicle has been investigated on the curve test. The vehicle’s overall performance has been investigated on the Highway Patrol Academy Track.

The computational method of Adams View serves the purpose of reflecting accurate results depending on the size of the step. The results lead to the following conclusion:

1) The 3-D simulation results were significantly close to theoretical results between a 10% error. The 0.75 drag factor from the skid simulation result obtains a travel distance of 70.53ft which is similar to the real time CHP skid test.

2) The stability over a curve shows significant results. However, the simulation could be improved by making the model assembly more flexible.

3) The performance over the Highway Patrol Academy Track will provide valuable information to the CHP for future research and safety maneuver of their vehicles.

4) The differences on the results were due to mass distribution of the vehicle, tires and road conditions.

5) More complex models of the vehicle could be studied. However, the complexity will increase the time of the analysis.

6) The Adams kinematics simulation uses around 40,000 KB per simulation. It is important to ensure that the computer has enough memory to support the simulation before starting any study. It is recommend to use an external drive.
This simulation will be beneficial for the CHP, as validation for the performance calculations. Also, as a visual recourse to explain the performance of the vehicle. This thesis project will be the base for future vehicle dynamics analysis for other graduate studies.
Appendix A. Solidwoks

A. Extrude feature

Extrude boss/base allows to add thickness to a 2-D sketch. The Extrude boss/base is located on the features toolbar. The end condition is the parameter that causes the extrusion to stop. Solidwoks’ end conditions are blind, up to vertex, up to surface, offset from surface, up to body and mid plane. The blind and mid plane require depth distance. All the offset end condition’s options must specify the offset in the model. The reverse direction allows to change the direction of the extraction. Observe the preview for feature direction.

B. Revolve feature

Revolve boss/base allows to create a 3-D solid by revolving a 2-D sketch along an axis. The revolve feature is located on the features toolbar. The axis of revolving should be included on the 2-D sketch as a construction line. The end condition is the parameter that causes the extrusion to stop. Solidwoks’ end conditions are blind, up to vertex, up to surface, offset from surface, and mid plane. The direction is the amplitude in degrees of the revolving profile, this direction must be defined for blind and mid plane end conditions

C. Extrude cut feature

Extrude cut allows to remove parts of a solid model from a 2-D sketch. Mainly used to create hole. The extrude cut feature is located on the features toolbar. The end condition and options are the same as extrude boss/base feature.

D. Loft Feature
Loft boss/base creates a solid between different 2-D profiles. The profiles must be closed. The loft feature is located on the features toolbar. On the profile tap, the different profiles need to be in order. Used the down and up arrows to obtain the correct order of sequence. Add 3-D sketch curves to fit the loft to the desire shape.

E. Create plane

It is possible to create planes in any part of the model. Planes could be used for sketch or a simple view of the model. The create a plane is located on the reference geometry toolbar. For this project is need it to use two references. The first one, a coincident construction line from the curve sketch. The second one, an existing tangential plane (the top plane). Observe the preview to ensure the direction of the plane.

F. 3-D Sketch feature

The 3-D sketch allows drawing on any arbitrary line in a 3-D space. The 3-D sketch feature is located on the sketch tab.

G. Mates feature

A mate is a geometrical relationship between two solids in an assembly. On the mate tab, select the geometry features involve in the mate, and the type of mate. The mates used on this project were coincident, concentric, parallel, and tangential.
Appendix B. Nomenclature

\( x \) State vector.
\( u \) Input.
\( y \) System output.
\( F \) Reaction force.
\( M \) Momentum.
\( V \) Velocity.
\( a_1 \) Distance from vehicle front rear tires to center of mass.
\( a_2 \) Distance from vehicle back rear to center of mass.
\( C \) Vehicle’s center of mass.
\( m \) Mass of the vehicle.
\( g \) Gravity.
\( \dot{v} \) Acceleration.
\( h \) Height from vehicle’s center of mass to the ground.
\( L \) Vehicle’s full length.
\( e \) Coefficient of restitution.
\( \Delta v \) Change in velocity.
\( R \) Curve radius.
\( \Delta \) Central angle of the curve.
\( PC \) Initial point of the curve.
\( PI \) Point of tangent intersection.
\( PT \) End point of the curve.
\( T \) Tangent length.
\( M \) Middle ordinate.
E  External distance.

L  Length of the curve.
Appendix C. Event Data Recorder Information

The highway patrol police provided event data record information from a Ford Crown Victoria. The vehicle executed different police maneuvers around the Highway Patrol Academy track. The vehicle was equipped with a video Vbox, a Vbox IIISX, 3 GPS antennas, and cameras. The video Vbox a provides recording of the drive via two cameras with real time graphical. The Vbox IIISX measures the position, speed, acceleration, braking distance, lap time, slip angle, and pitch angle of the moving vehicle using the GPS antennas. The antennas need to be 50 inches from each other forming a triangle on top of the vehicle. The following figures C.1 to C.3 shows the vehicle equipment.

Figure C.1 Video Vbox vehicle mount
After the vehicle test, the information from the Powertrain Control Module (PCM) and an Airbag Control Module (AMC) was obtained the Crash Data Retrial system (CDR). Figure C.4 show the CDR. Figure C.4 shows the PCM on the vehicle.
Figure C.4 Crash Data Retrieval system (CDR)

Figure C.5 Powertrain Control Module (PCM) on the vehicle
Bibliography


