MODELING CRITICAL OVERTURNING CRITERIA FOR SINGLE VEHICLE RUN-OFF-ROAD CRASHES FOR BANGLADESH CONTEXT

by

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Abstract

Road traffic accidents and the consequent deaths are the most concerning issue in the transportation sector of the world. Being a developing country Bangladesh is not an exception. The road safety situation in Bangladesh is very severe by international standards. Accident and casualty statistics of 13 years (1998-2010) shows that overturning accident is about 9% of total accidents and is responsible for 15% of total fatalities. Analysis in Microcomputer Accident Analysis Package (MAAP5) demonstrates that overturning of vehicles to the left or right of carriageway on straight or curved road comprises of about half of the single vehicle Run-Off-Road (ROR) crashes in Bangladesh.

Running off road may not be the sole result of driver performance, rather it is due to the result of complex interaction among vehicle loading pattern, tire characteristics, improper super elevation, cross slope, vehicle speed etc. Shoulder or pavement edge drop-off, discontinuity in shoulder, ill-maintained road/shoulder surface also imposes potential safety hazards. When left wheels go onto the shoulder, the drop-off causes tilting of vehicle and in effect the resultant moment increases that tends to overturn the vehicle. Vehicle speed and overloading condition are the other factors that may affect the stability of vehicles. While the vehicle is in motion, it undergoes continuous jerking and vibration effect from the potholes and rough road surface. If the loading is loosely fastened and is of high height, bulging and shifting of load occurs. Due to this, the horizontal component of CG gradually shifts towards the direction of roadway slope that makes a vehicle more prone to overturn. High centre of gravity height may worsen the situation.

Considering these facts, in this research work, an analytical model is developed which relates these factors with ROR crashes and establishes critical condition for overturning in terms of rollover threshold. The rollover model deals with shoulder drop-off as special geometric feature, vehicle speed as driver behavior, gross weight, overall height and load bulging as vehicular features. Some guidelines are also provided based on the model analysis. Though ROR crashes involving buses result in more fatalities and casualties, considering importance of freight transportation, the model covers only heavy truck features. Matlab/SimuLink is used for the simulation of the model.

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	0	1	2	3	4
	PEDESTRIAN on foot, in toy/pram	INTERSECTION vehicles from adjacent approaches	VEHICLES FROM OPPOSING DIRECTIONS	VEHICLES FROM ONE DIRECTION	MANEOUVRING
	OTHER 000	OTHER 100	OTHER 200	OTHER 300	OTHER 400
				VEHICLES IN SAME LANE	
1	NEAR SIDE 001	THRU–THRU 101	HEAD ON 201	REAR–END 301	LEAVING PARKING 401
2	EMERGING 002	RIGHT–THRU 102	THRU–RIGHT 202	LEFT–REAR 302	PARKING 402
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5	WALKING WITH TRAFFIC 005	RIGHT–RIGHT 105	THRU–LEFT 205	VEHICLES IN PARALLEL LANES LANE SIDE SWIPE 305	REVERSING INTO FIXED OBJECT 405
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9	STRUCK WHILE BOARDING OR ALIGHTING 009	LEFT–LEFT 109		LEFT TURN S/S 309	
10					

Fig. 5 — Definitions for coding accidents - left hand version (1994)

Fig. 5 — Definitions for coding accidents - left hand version (1994)

APPENDIX II

Photographs Showing Bulging of Loading

960x720 88kb JPEG

APPENDIX III

Yearly Distribution of ROR Accident and Casualty

Year	Accident			Casualty			Casualty/Accident
	Fatal	Non Fatal	Total	Fatality	Injury	Total	
2006	143	40	183	239	302	541	2.96
2007	89	39	128	120	185	305	2.38
2008	114	37	151	209	262	471	3.12
2009	75	19	94	119	108	227	2.41
2010	84	14	98	171	189	360	3.67
Total	**505**	**149**	**654**	**858**	**1046**	**1904**	**2.91**
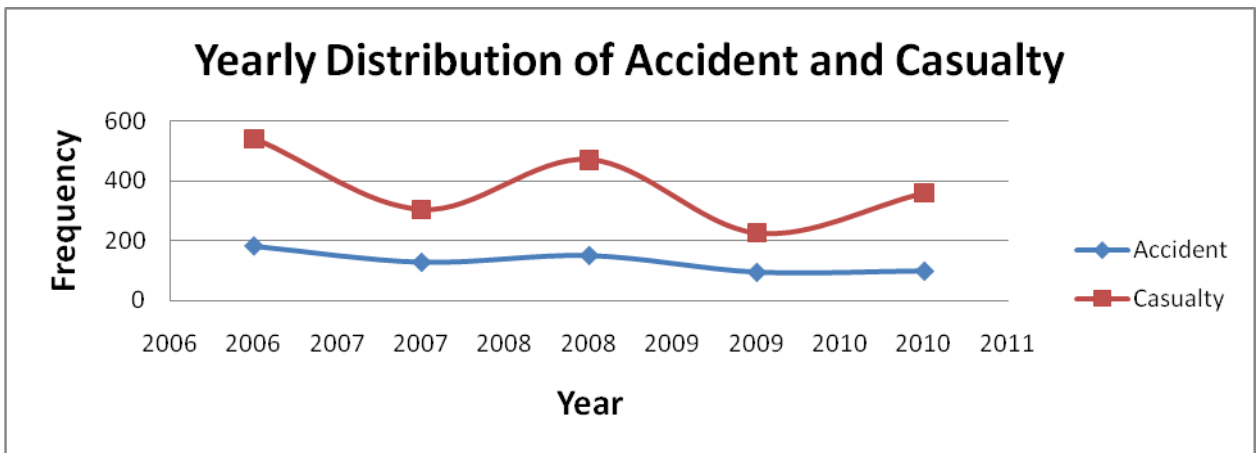
Yearly Distribution of ROR Accident and Casualty
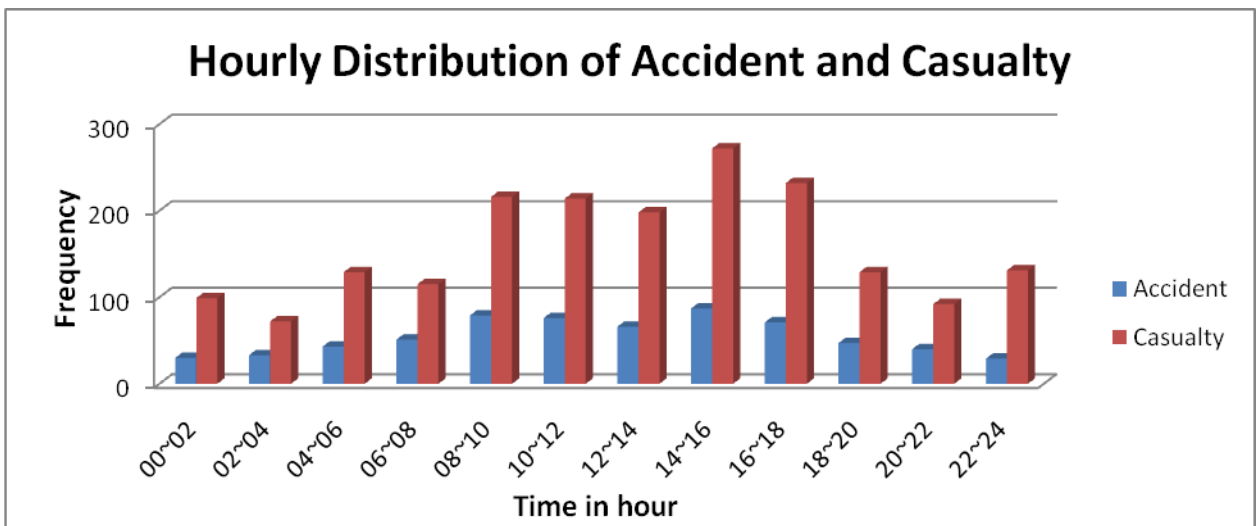
Hourly Distribution of ROR Accident

ROR Accident in Different Road Surface Condition

Surface Condition	Accident	Casualty	Casualty/Accident
Dry	571	1626	2.85
Wet	67	241	3.60
Muddy	4	4	1.00
Flood	1	3	3.00
Other	9	25	2.78
Total	**652**	**1899**	**2.91**
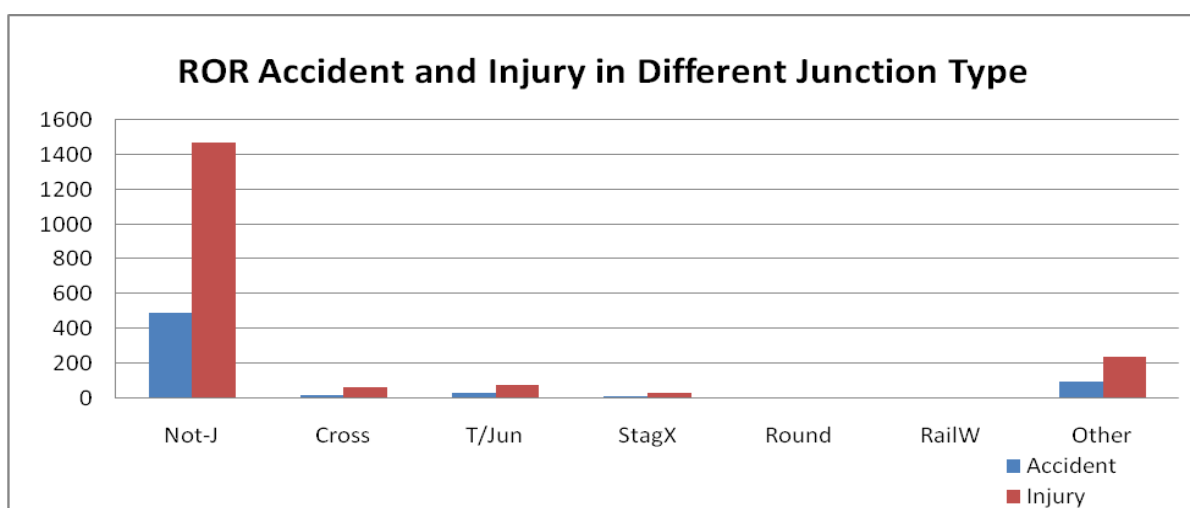
Distribution of ROR Accident and Severity in Different Types of Junction

Distribution of ROR Accident in Different Road Class

Road Class	Accident	Casualty	Casualty/Accident
National	290	800	2.76
Regional	109	350	3.21
Feeder	150	422	2.81
Rural	85	282	3.32
City	17	38	2.24
Total	**651**	**1892**	**2.91**

ROR Accident in Different Road Geometry

Road Geometry	Accident	Casualty	Casualty/Accident
Straight	516	1482	2.87
Curve	66	180	2.73
Slope	19	46	2.42
Curve & Slope	38	148	3.89
Crest	12	37	3.08
Total	**651**	**1893**	**2.91**

Distribution of ROR Accident by Different Road Features

Road Feature	Accident	Casualty	Casualty/Accident
None	596	1695	2.84
Bridge	25	115	4.60
Culvert	12	32	2.67
Narrow	12	33	2.75
Speed breaker	3	10	3.33
Total	**648**	**1885**	**2.91**
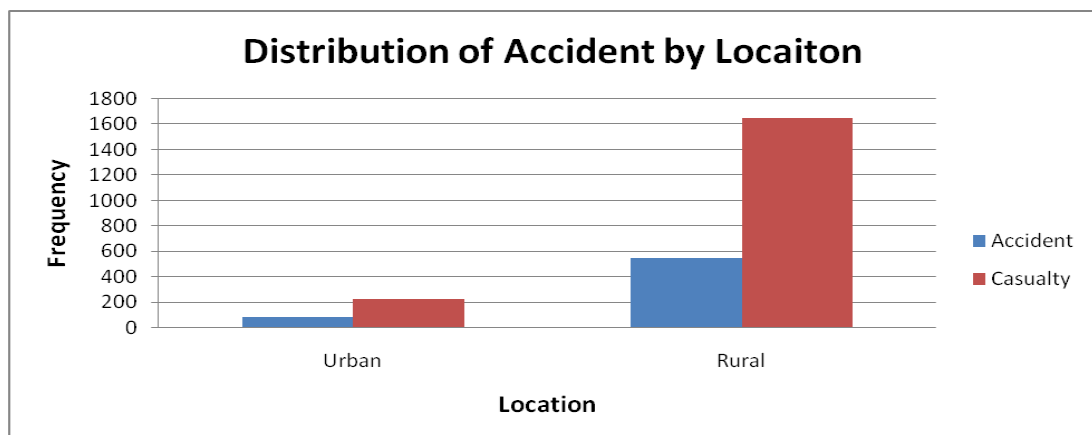
Distribution of Accident by Location

Distribution of ROR Accident by Highway Route

Highway	N1	N2	N3	N4	N5	N6	N7	N8	N9
Accident	37	23	13	14	55	8	11	19	11
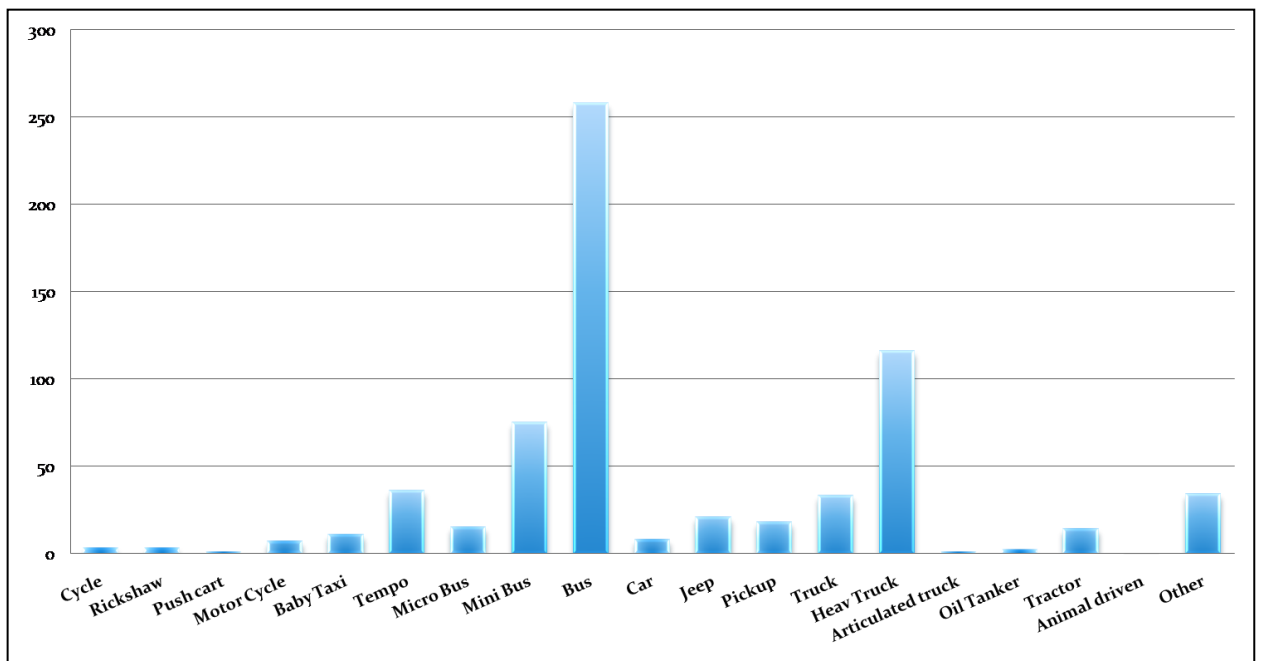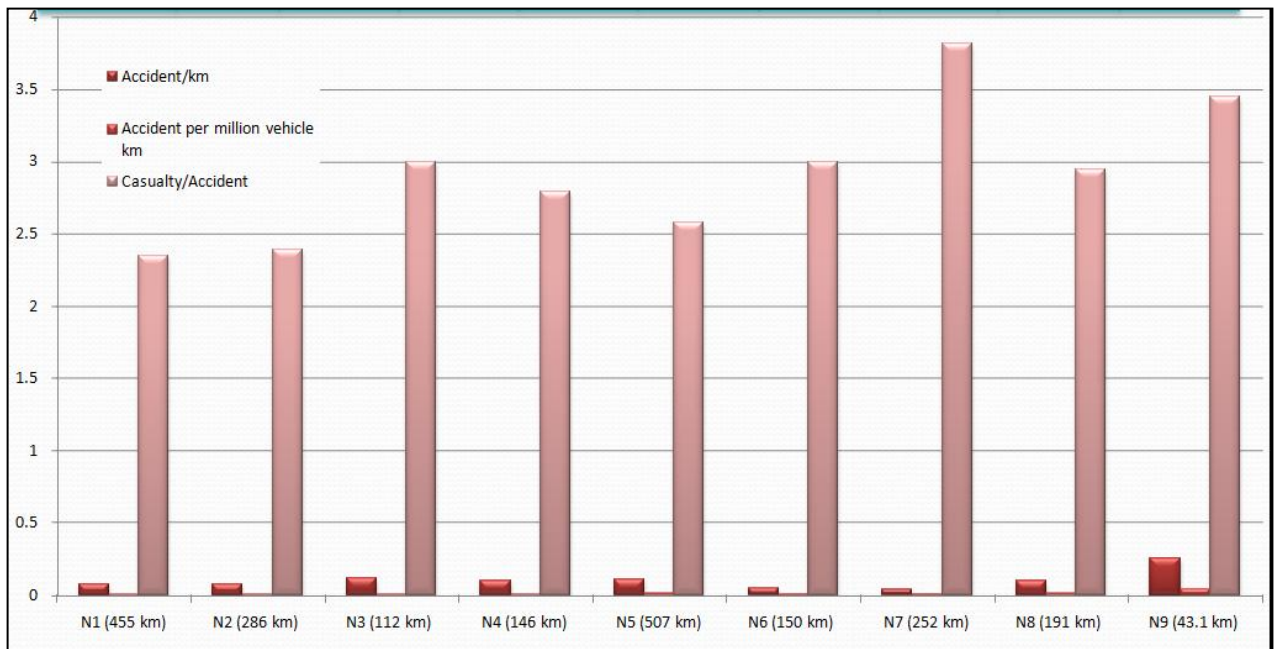
Vehicular Involvement in ROR Accident by Vehicle Type
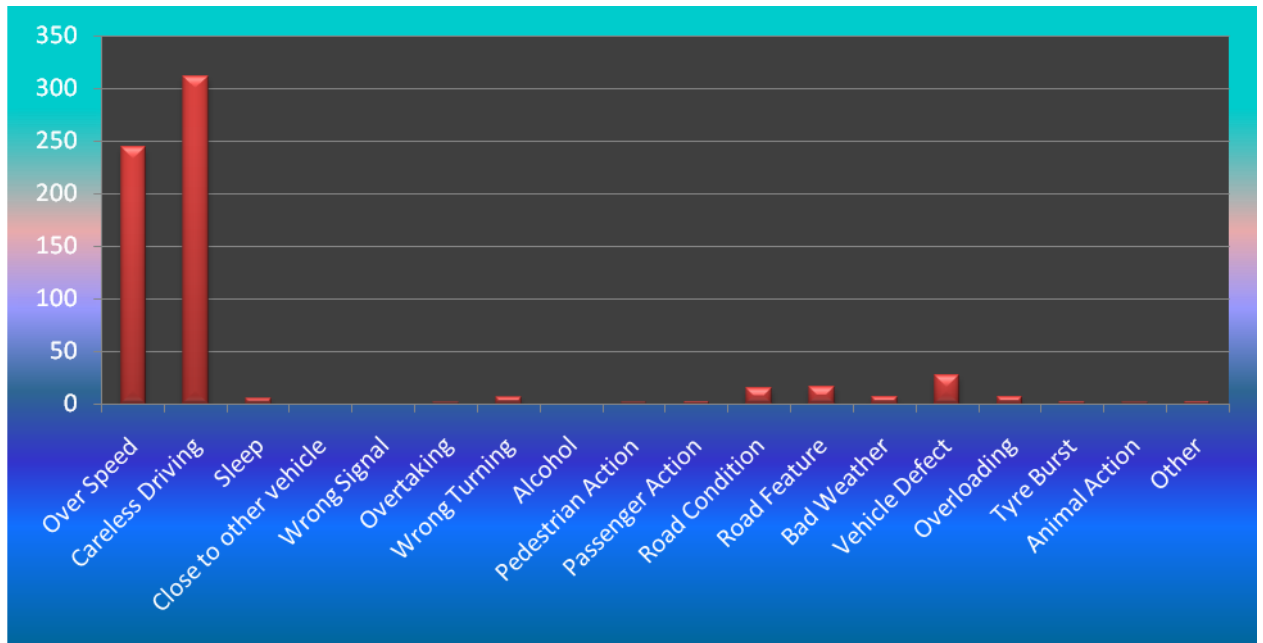
Contributing Factors in Run-off-road Accident

CHAPTER 1

INTRODUCTION

1.1. Background

Road traffic accidents and the consequent deaths are the most concerning issue in the transportation sector of the world. According to WHO Report 2009, More than 1.2 million people die each year on the world's roads, and between 20 and 50 million suffer non-fatal injuries. Over 90% of the deaths occur in low and middle income countries [1]. Being a developing country the road safety situation in Bangladesh is very severe by international standards with approximately 160 deaths per ten thousand motor vehicles whereas the rate in the USA is only 2 and in the UK it is 1.4 [2]. It has been rapidly deteriorating with increasing number of road accidents as well as deaths. Rapid growth in population, motorization and urbanization has a direct consequence on road accident. According to police reported road traffic accident database, every year about 4000 people are killed in around 3500 or more accidents in Bangladesh. But the actual estimated road fatalities are as high as 10,000-12,000 each year.

1.2. Motivation of the Work

Of the various types of accidents occurring on road, Head-On, Rear-End, Overturning, Side-Swipe and Hit-Pedestrian are the most dominant. Accident and casualty statistics of 13 years (1998-2010) shows that, these five types account for nearly 90% of total accidents and 90.25% of total fatalities. Though the number of fatal overturning crashes is much less than that of others its consequences is more alarming. Considering deaths per accident, it is noticed that overturning crashes (fatality index 1.97) are more serious than the others (head-on: Fatality Index (FI) 1.69; side-swipe: FI-0.99; rear-end: FI-0.9; hit-pedestrian: FI-0.88). Yearly distribution of fatality/acc shows a much more increasing trend of overturning accident than that of others for the last four years. Fatal overturning accident (9% of total fatal accident) accounts for almost 15% of all fatality.

Running of road may occur in any of these accidents as an aftermath. These accidents are categorized into ten groups of accident types, coded from 0 to 9 according to the Road User Movement (RUM) code. Their schematic classification is given in Appendix I. The accident types 0 to 6 and 9 include accidents where a vehicle collides

with another traffic participant, animal or object. Type 7 and 8 is designated as 'Non Collision on Straight' and 'Non Collision on Curve' respectively. These two types of accidents are further subdivided according to whether the vehicle runs off to the left or right or off carriageway into roadside object or out of control on carriageway. Based on this differentiation, the accident type 7 and 8 is coded into 700, 701, 702 … 707 and 800, 801….805 as shown in Appendix 1. In this thesis, the overturning accidents on which a vehicle leaves off the road are referred to as single vehicle run off road (ROR) accidents.

Numerous studies have been carried out on single vehicle Run-off-road crashes in developed as well as in some developing countries like Malaysia and Thailand. ROR crashes have been considered as a serious safety concern in all the research works. The researchers have identified various factors and established static and dynamic relationship with rollover propensity. They developed various models mathematically and interpreted the outcomes with real world scenario. And finally, they propose some specific countermeasures.

For instance, Pomerleau D. et. al. 1997, SWOV article, 2012 and Abidin A.N.S.Z. et al. 2009 pointed out that ROR crashes are the most serious of crash types in the USA, the Netherlands and Europe with 39%, 33% and 33% fatal crashes respectively [3,4,5]. The NCHRP Report, 2003 has described some specific goals for keeping vehicles on road and for minimizing the consequences of leaving the road [6]. An ARRB publication has listed some known causes of ROR crashes [7].

According to these studies the factors contributing to ROR crashes are related to **driver's characteristics** like drink-driving, inattentiveness, sleepiness, speeding etc., **road geometric feature** like numbers of carriageway, pavement quality, lane and road shoulder width, shoulder drop-off, curve etc., **road environment** like presence of poles, trees, walls, or embankments etc., and **vehicular factors** like overloading, brake failure, tire burst etc. Gillespie T.D. and Ervin R.D. (1983) and Gillespie T.D. (1992) developed various rollover models mathematically and interpreted the outcomes with real world scenario [8,9].

In terms of the transportation system, socio-economic condition, driver characteristics, road geometric condition, vehicle modification etc. Bangladesh is a

country with some special peculiarities that differs a lot from the others. Identification of root causes and providing countermeasures are always area and site specific. Hence, the factors may not be the same as in other countries. In Bangladesh various research have been made previously that are related to finding general accident characteristics, identification and investigation of hazardous locations, evaluating involvement of drivers, pedestrian accident etc. But no study on run off road collision has been carried out in our country. This may be the first effort dealing with this type of collision.

Accident analysis in MAAP5 software shows that vehicle leaving the road to the left and fall outside has the largest share in both accidents and fatalities. It comprises of about 42% of all ROR crashes and 46% of all ROR crash fatalities. Vehicles involving in ROR crashes are usually bus-minibus (42.42%) and truck-heavy truck (28.69%). Around 7.5% buses and 15% trucks are overloaded at the time of ROR accident.

Considering these facts in this study an attempt has been made to co-relate special geometric and vehicular features with ROR crashes as critical overturning criteria by developing analytical model as well as a comprehensive and detail analysis on ROR crashes.

1.3. Significance of the Study

It is expected that the outcome of this research can be used to address the influence of special geometric and vehicular factors causing run-off-road crashes in Bangladesh context. The research would be helpful in providing engineering countermeasures. The results can also be used to direct additional research into specific areas of need identified by this research.

1.4. Objectives of the Study

The overall objective of the study is to analyze the characteristics of Run-off-Road accidents occurring in national highways of Bangladesh. The study in particular aimed at assessing special geometric and vehicular features in rollover accident. The specific objectives of the study are:

- To critically review various aspects of run-off-road accident on the basis of analysis with Microcomputer Accident Analysis Package (MAAP) software.

- To develop critical overturning criteria in terms of Rollover Threshold - a function of centre of gravity height, its horizontal eccentricity and track width of heavy vehicle.

- To establish a relationship of shoulder drop-off and bulging effect of loading with rollover accident.

- To correlate speed and weight of vehicle with rollover.

- To provide some specific guidelines for overloading height, shoulder drop off, loading pattern etc. to reduce the probability of overturning.

1.5. Organization of the Study

Apart from this chapter, the remainder of this study report is divided into six chapters as follows:

- Chapter 2 reviews the literature relevant and related to the theme of this study. Aspects considered include worldwide run-of-road accident problems, the causal factors and their safety relationships and some recommended measures. It also covers a review of literature on the rollover models.

- Chapter 3 presents methodological description and data collection process. This chapter outlines a framework of developing a mathematical model for diagnosing run-off-road crashes in highways of Bangladesh. It also describes the road geometric and vehicular data for model calibration.

- Chapter 4 covers accident data analysis in MAAP5 software. It also describes the process of model development along with analysis.

- Chapter 5 describes the validation process. In this research work the model is validated by simulation in MATLAB using SimuLink tool.

- Recommendations are summarized in Chapter 6 by drawing study conclusions and suggestions. Direction for future research and major policy issues regarding road geometry with the safety are also discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter documents the literature review performed on roadway departure or run-off- road (ROR) crashes. It summarizes key studies that have been conducted in various developed and developing countries. This chapter is divided into seven sections. The first section describes various studies on single vehicle ROR crashes in home and abroad. The second one is about characteristics and the magnitude of the problem associated with ROR crashes. The third portion summarizes the contributing factors related to ROR crashes that have been reported in the literature. The fourth section outlines countermeasures previously evaluated for reducing the number and severity of roadway departure crashes. The fifth part covers rollover of heavy vehicles. The sixth section discusses about rollover threshold from various literatures. And the last segment summarizes a range of mathematical models of rollover dynamics that have been reported in several literatures.

2.2 Study on Single Vehicle Run-Off-Road Crash in Home and Abroad

Single vehicle run-off-road (ROR) crashes involve vehicles that leave the travel lane and encroach onto the shoulder and beyond and either overcorrects, overturn, hit one or more of any number of fixed or non-fixed objects, or otherwise result in a harmful event to the vehicle occupants or other persons [10].

According to the Central Library, Civil Engineering Library and Accident Research Institute (ARI) Library of BUET, various research have been carried out previously in Bangladesh that are related to finding general accident characteristics, identification and investigation of hazardous locations, evaluating involvement of drivers, pedestrian accident etc. But no study on run off road collision had been carried out in our country. It may be the first effort.

Numerous studies had been conducted on run-off-road accidents around the world. Among various researchers T.R. Neuman, C.V. Zegeer, G. Glennon, T.D. Gillespie are found to be prominent in the field of ROR and rollover research. University of Michigan Transport Research Institute (UMTRI) was the premier in conducting study on roadway departure crash in the 80s and the 90s. National Highway Traffic Safety

Administration (NHTSA), Federal Highway Administration (FHWA), The National Cooperative Highway Research Program (NCHRP) of Transportation Research Board (TRB) carried out a number of research work on rollover safety. All the works had been done to investigate and address ROR crashes and their consequences, to identify the effects of various factors on such accident type and to provide some countermeasures after real life experimentation. The following sections of this chapter would be helpful to clarify the research findings.

2.3 Accident and Injury Statistics involving Run-Off-Road Crashes

Run off road crashes have always been a serious safety concern around the world as they account for a large number of fatal crashes and fatalities each year. Researchers have identified ROR crash as an important leading cause of traffic fatalities on highways. A statistical review of the 1992 General Estimation System (GES) and Fatal Accident Reporting System (FARS) databases indicate that run-off-road crashes are the most serious of crash types within the US crash population. These crashes account for over 20% of all police reported crashes, and over 41% of all in-vehicle fatalities (15,000 / year) [11]. In 1999, Neuman et al. (2003) reported that nearly 39 percent of all fatal crashes (all road types) were classified as single-vehicle ROR crashes [12]. According to FHWA (2006) [13], in 2005, over 25,000 people were killed because drivers left their lane and crashed with an oncoming vehicle, rolled over, or hit an object located along the highway. Of all these fatalities, it is estimated that about 17,000 were the results of a single-vehicle ROR crash; this type of crash accounts for about 60 percent of all fatalities on the U.S. highway network. It is estimated that the societal costs associated with ROR crashes are 2.53 times more compared to other accidents [14]. The social costs amount to more than 1 trillion dollars per year.

2.4 Contributing Factors of Run-Off-Road Crash

A study of Calspan Corporation conducted in 1994, showed that ROR crashes on both straight and curved roads were caused by the six major factors: driver inattention (e.g., retrieving a fallen object), driver relinquished steering control (i.e. heart attack or intoxication), excessive vehicle speed, evasive maneuver, loss of directional

control on road surface (i.e., slippery surface due to rain or snow), and vehicle failure (e.g., tire blowout or loss of power steering). The driver's ability and willingness to perform the required task play a role in the majority of run-off-road crashes. [15]

Another recent ARRB publication [16] has listed some known causes of ROR crashes, which include:

- Driver behaviors such as speed, inattention, avoidance maneuvers, errant vehicles

- Driver impairment including fatigue, alcohol, drugs, mood state

- Road conditions such as horizontal alignment, shoulder deficiencies (e.g. excess loose material or steep edge of seal drop-off), slippery surface, poor delineation, damaged surfaces

- Vehicle failure

- Environmental conditions such as rain, fog, snow, livestock or native fauna.

So we can group the components of the ROR crash factors as the roadway itself, the vehicle and the driver. These components, considered together, are a system that must operate in harmony. Each component of the system has limitations and is subject to failure.

2.4.1 Road Geometric Factor

Most of the elements of road infrastructures have significant effects on ROR incident. It can be categorized by lane width, shoulder width, shoulder drop-off, horizontal and vertical alignment, surface friction, roadside features etc.

Lane Width:

Several researchers have investigated the safety effects associated with lane width and roadway departures. Overall, the studies tend to show that narrower lane widths are associated with an increase in roadway departures, at least for lane width below 12 ft. In the research work R. Elizabeth Abel identified that ROR crashes are more frequent on narrower lane (<10 ft), with steep grade and on sharp curved road. He showed increased lane width and shoulder width have positive impact on ROR crashes [17].

Shoulder width:

Several studies have examined the relationships between shoulder width and ROR crashes. The studies indicated that increasing the shoulder width decreases the crash rate. For instance, Zegeer C.V. and Deacon J. (1987) reported that shoulder width had a notable effect on accident rate. They developed a model to predict the crash rate as a function of lane width, shoulder width, and shoulder type [18]. Ornek E. and Drakopoulos A. (2007) analyzed crash data on rural highways in Wisconsin and mentioned that for rural two-lane undivided highways, wider paved and unpaved shoulder widths were associated with the lowest ROR crash rate [19].

Shoulder Drop-off:

Shoulder drop-off on highways has been linked to many serious crashes, including fatal collisions. Drop-offs occur when there are height differences between a paved road and the adjacent graded material. Conventional paving techniques result in vertical or nearly vertical pavement edges, which can cause safety concerns when they are exposed. When a vehicle leaves the traveled way, pavement edge drop-off poses a potential safety hazard because vertical differences between surfaces can affect vehicle stability and reduce a driver's ability to handle the vehicle.

Internationally there is not much data on shoulder drop-off related accidents, and in Bangladesh no data is available. In Iowa, pavement edges may have contributed to as many as 18% of rural run-off road crashes on paved roads with unpaved shoulders during 2002-2004. In Missouri, that percentage was nearly 25%. Using data from Iowa and Missouri and performing regression analyses, Hallmark et al. (2006) noted that the risk of crashes becomes problematic when the edge drop-off is larger than 2.0 inches. Thus, the authors suggested that the maintenance threshold should be maintained at a dimension less than 2.0 inches [20]. Glennon G. (1987) noted that a 5-inch drop-off height was the practical maximum to prevent hazardous undercarriage contact on most vehicles [21]. The FHWA indicates that drop-offs of three or more inches can be considered dangerous (Roche J. 2009) [22].

Horizontal and Vertical Alignment:

It is generally assumed that vehicles will more easily leave their lane on a curve rather than tangent section because of the centrifugal force that acts on the vehicle when it enters the curve. However, Zegeer C.V. et al., (1987) have stated that there seems to be no difference between the number of crashes occurring on tangents and on curves [23]. On the other hand, Glennon J.C. et al., (1985) have found that the risk of leaving the traveled way on a curve is about 1.5 to 4 times higher than on a tangent segment [24].

For vertical grades, some researchers have reported that steeper grades are associated with an increase in crashes [25].

Surface Friction:

The low friction of pavement can cause vehicles to skid and run off the road. Based on a study performed in New York, Neuman T.R. et al. (2003) reported that low skid resistance increases crash risk on wet pavement by 50 percent [12].

Roadside Features:

An NCHRP report [12] prepared by Neuman T. R. et al. (2003) summarized the effects of roadside features on the severity of ROR crashes. The top four roadside features that led to fatal crashes were as follows: overturn (42%), an impact with a tree (26%), an impact with a utility pole (7%), and an impact with a ditch or embankment (5%). The report also noted that objects located near the roadside may harm the errant drivers more seriously than objects located further away, especially on high-speed roads.

2.4.2   Vehicle Factor

Compared to passenger cars, trucks usually have a high center of gravity. Hence, this type of vehicle has a greater risk of rolling over in the event of an ROR crash. To this effect, Farmer C. and Lund A. (2002) examined FARS crash data for the period of 1995–1998 and found that risk to roll over of light trucks (pickups, vans, and SUVs) were twice as likely as cars, following a roadway departure [26].

2.4.3   Driver Characteristics

Though driver's ability to control the vehicle can be affected by the roadway conditions, some ROR incidents may be occurred when the laws of physics overcome a driver's ability to control the vehicle.

On the basis of a research conducted by Liu C. and Subramanian R., some of the driver performance-related factors that are likely to contribute to the occurrence of ROR crashes were: (1) sleepy (drowsy, asleep, fatigued, and sleepy); (2) inattentive (talking, eating, etc.); (3) over-correcting of the vehicle; (4) avoiding (avoiding, swerving, or sliding due to severe crosswind, tire blow-out or flat, live animals in road, vehicle in road, etc.); (5) distractions inside vehicles (cellular telephone, computer, fax machine, etc.); and (6) other driver-performance-related factors, such as mentally challenged, following improperly, failure to signal intensions. [27] However driver's age, sex or speeding behavior was not included in their study.

SWOV Article, January 2012 issue stated that the drivers involved in ROR crashes were mainly young, inexperienced male drivers who took a bend too fast which was poorly delineated, or who overtook when this could not safely be done and consequently crashed into a tree or other obstacle. McGinnis R. et al. (2001) found that male drivers have a higher ROR crash rate than female drivers. Compared to mid-age female drivers, the ROR rate for teenage males is about 20 times higher and for teenage females 9 times higher [28].

Davis G. A. et al. (2006) summarized the literature related to the relationship between speed and ROR crashes on rural two-lane highways. They indicated that the relative risk of a serious or fatal ROR crash clearly tended to increase as speed increased [29]. In a recent study, Liu C. and Ye T.G. (2011) reported that 25 percent of the driver-related factors were attributed to driver decision errors, most of which included speeding drivers [30].

2.5 Countermeasures for reducing Run-Off-Road Crash

The National Cooperative Highway Research Program (NCHRP) has developed a number of guidelines relevant to ROR collisions. A multi volume report (NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety

Plan) provides guidance for implementing a strategic highway safety plan. The sixth volume of this report provides strategies that can be employed to reduce the number of run-off-road collisions. In this report the countermeasures are grouped according to three general objectives: i) keep vehicles from encroaching on the roadside; ii) minimize the likelihood of crash or overturning if the vehicle leaves the traveled way; and, iii) reduce the severity of a crash. Each countermeasure was evaluated and rated as "Tried," "In Experimental Stage," or "Proven."Volume 3 (Neuman T.R., 2003a) of the same report addresses tree collisions in particular, and Volume 7 addresses issues related to roadway curvature and presented strategies to minimize collisions on horizontal curves (Neuman T.R., 2004).

Parkhill M. (2006) stated that both the severity and frequency of run-off-road collisions may possibly be reduced through roadway and roadside design. The frequency of ROR collisions can be managed by roadway characteristics that facilitate maintaining the lane or recovering of the lane. And the severity of these collisions can be managed by roadside design that is "forgiving"; i.e. roadsides that are clear of obstacles which might be unavoidable for a driver who has left the roadway [31].

This section briefly summarizes countermeasures that have been proposed in the literature for reducing the number and severity of ROR crashes.

Lane and Shoulder Widening

Zegeer C.V. et al. (1981) conducted a study to determine the effect of lane width and shoulder width on safety benefits for rural two-lane highways. Using the before-after study approach, they found ROR and opposite-direction crashes to be associated with narrow lanes and shoulders. They reported that widening lane and shoulder widths could significantly reduce crashes. For instance, widening the traveled way (lane and shoulder width) by 4 ft could reduce related crashes by up to 20 percent [14].

Nambisan S. and Hallmark S. (2011) cited a study conducted by Harwood et al. (2000) that the authors found that wider shoulders tended to have fewer crashes on rural two-lane highways [32].

Agent K.R. et al. (2001) analyzed crash data (1996-1998) in Kentucky and noted that adding a shoulder and increasing shoulder width are very effective at reducing roadway departure crashes [33].

Safety Edge for shoulder drop-off

The most common solution to pavement edge drop-off is maintenance of unpaved shoulders. The use of the safety edge helps vehicles to return to roadway safely. The Safety Edge is a design feature that creates a fillet along the outside edge of the paved section of a roadway. Humphreys J.B. and Parham J.A. (1994) suggested that a 45 degree angle asphalt fillet placed at the lane edge would be useful in addressing over-corrections, even for unpaved or eroded shoulders [34]. Neuman T.R. et al. (2003) also suggest creating a 45 degree wedge during pavement resurfacing in their NCHRP 500 series report.

Shoulder Rumble Strip

According to the FHWA, shoulder rumble strips are proven safety countermeasures for reducing lane departure i.e. ROR crashes. Rumble strips are raised or grooved patterns placed in the pavement surface perpendicular to the direction of traffic. The interaction between the tires and rumble strips creates both an audible warning (rumbling sound) and physical vibration, which alert the driver that they are leaving their lane, so they can take corrective actions. Rumble strips can be installed on a paved shoulder (shoulder rumble strips) or on the pavement edge line (edge-line rumble stripes) [32].

Neuman T.R. et al. (2003) reported that rumble strips could reduce the ROR crash rate by 20 to 50 percent on urban and rural freeways. It is anticipated that a reduction in ROR crashes would also be observed on rural two-lane highways [12].

Based on a comparison of three years of before-after data, Smith E. and Ivan J. (2005) found that installing the rumble strips reduced single-vehicle fixed-object crashes by 33 percent and ROR crashes by as much as 48.5 percent [35].

In a recent study, the American Traffic Safety Services Association (ATSSA) (2006) found that, in Mississippi, installation of edge-line rumble strips on a two-lane roadway resulted in a 25 percent reduction in right-side ROR crashes.

Raised Pavement Marking

Raised pavement marking (RPM) can provide drivers a clear delineation of the roads and enhance their ability to track the roadway, especially in dark or during wet weather conditions.

Lord D. et al. (2011) cited the following table that summarizes the studies analyzed by ATSSA in 2006 [36].

Table 2.1: Study Summary by ATSSA

Study	Year	Location	Key Study Results
Wright, et al. (1982)	1970	Georgia	1. RPMs reduced nighttime crashes by 22% compared with daytime crashes at the same sites. 2. RPMs reduced single-vehicle crashes by 12% more than other nighttime crash types.
Neuman, et al. (2003)	1970	Ohio	1. RPMs reduced the total and injury crashes by 9% and 15%, respectively. 2. RPMs provided positive benefits for different kinds of driving conditions, including dark (a reduction of 5%) and wet weather (a reduction from 6% to 11%). 3. The ratio of benefit and cost of RPMs was 6.5 to 1.
Neuman, et al (2003).	1980	New Jersey	The calculated benefit-cost ratios ranged from 15.49 to 1 to 25.51 to 1.
New York State Department of Transportation (1997)	1990	New York	1. RPMs decreased the total number of crashes by 7%, nighttime crashes by 26%, and nighttime wet weather crashes by 33%. 2. For guidance related crashes (e.g., run-offroad, head-on, encroachment, and sideswipe), RPMs reduced all crashes by 23% and nighttime crashes by 39%.

Bahar, et al. (NCHRP Project 5-17)	2004	Six states	In New York, RPMs reduced the total number of crashes by 10%, nighttime crashes by 13%, wet weather crashes by 20%, and wet and nighttime crashes by 24%.

Roadside Delineators

Neuman T.R. et al. (2003) mentioned that enhanced delineation on sharp curves can reduce ROR crashes. Examining several studies in the U.S. and other countries, they reported that post mounted delineators could reduce ROR crashes by 15 percent on curves [12].

Installation of Guardrail

Paulsen T.J. et al. (2003) performed various crash tests and showed that energy-absorbing terminals greatly reduce the velocity of small vehicles. A 75 percent reduction in speed was observed for head-on impacts and approximately 50 percent when the terminal was struck at an angle of 15 degrees [37].

Improving Horizontal Curves

Neuman T.R. et al. (2003) summarized previous research on the effectiveness of flattening horizontal curves for different scenarios. They indicated that by reducing the degree of curvature, the number of ROR crashes reduced [12].

Intelligent Transportation Systems (ITS)

Many researchers have evaluated the effectiveness of ITS for helping drivers maintain control of their vehicle and avoid running off the road. For instance, Rimini-Doering M. et al. (2005) examined the effectiveness of the Lane Departure Warning (LDW) system and found that the LDW system can prevent up to 85 percent of the lane departure events caused by a driver falling asleep behind the wheel [38].

2.6 Rollover and Heavy Vehicle

Rollover accidents of heavy vehicles are especially violent and cause greater damage and injury than other accidents. Moreover it imposes intense damage on freight and vehicle. Thus rollover accidents have a direct consequence on the economy of a country. For such reason rollover of heavy vehicles has been considered as a serious safety concern all over the world.

A lot of studies have been carried out on rollover crashes of heavy vehicles in different countries. Especially developed countries have played the leading role in such research. Considerable efforts have been made to address the causes of overturning and to suggest corresponding possible countermeasures.

The direct cause of rollover is something that increases the roll moment about the longitudinal axis of the vehicle, generally either turning too quickly or allowing one side of the vehicle to drop or rise suddenly. High center of gravity is a major factor that increases the roll moment and contributes to the vehicle's likelihood of overturning.

Dilich M.A. and Goebelecker J.M., (1997) [39] listed the range of rollover causes for heavy vehicles. The great majority were driver errors, including excessive speed in curves, drifting off road, misjudging sharpness, counter-steering abruptly, being impaired physically (e.g. fatigue, drowsiness) or emotionally (reckless, angry). Vehicle-related problems include heavily loaded with badly distributed or unsecured loads, poorly maintained brakes or suspension and under-inflated tires.

2.7 Rollover Threshold

To what extent a vehicle is prone to rollover or overturning is determined by a term "Rollover Threshold". Rollover threshold or Static Rollover Threshold (SRT) is defined as the maximum lateral acceleration a vehicle can sustain without overturning or the least lateral acceleration at which a vehicle is starting to overturn. Usually this lateral acceleration is measured in g's and expresses as a_y.

Therefore, Rollover Threshold, SRT = a_y/g

Often rollover threshold is termed as Static Stability Factor, SSF. It is expressed as 'T/2h', where 'T' is the track width or tread of the vehicle and 'h' is the centre of gravity height. The lower the value of SSF or rollover threshold, the higher the risk of rolling over.

Gillespie T.D. (1994) listed a chart of varying rollover threshold with centre of gravity height and track width for different vehicle types [9]. The list is given below. It is clearly perceived that heavy truck is in greater risk to rollover.

Vehicle Type	CG Height	Tread	Rollover Threshold
Sports car	18-20 inches	50-60 inches	1.2-1.7 g
Compact car	20-23	50-60	1.1-1.5
Luxury car	20-24	60-65	1.2-1.6
Pickup truck	30-35	65-70	0.9-1.1
Passenger van	30-40	65-70	0.8-1.1
Medium truck	45-55	65-75	0.6-0.8
Heavy truck	60-85	70-72	0.4-0.6

Figure 2.1: Chart of Rollover Threshold of Different Vehicles

The SSF is used by the National Highway Traffic Safety Administration (NHTSA) to determine crash testing and rollover ratings. The agency introduces 'Star Rating' corresponding to risk of rollover. Based on the statistical model NHTSA suggests a rating arrangement on the basis of SSF value. According to this categorical distribution, vehicles with SSF below 1.15 fall in the 3 star rating group and vehicles with a SSF above 1.35 place in 4 star group or above. The rating system demonstrates that the higher the rating, the higher the SSF value i.e. the vehicles are in less rollover risk.

Table 2.2: NHTSA Star Rating and Rollover Risk

Rating Description	Rollover Risk
5-star	rollover risk of less than 10%
4-star	rollover risk between 10% and 20%
3-star	rollover risk between 20% and 30%

2-star	rollover risk between 30% and 40%
1-star	risk of rollover greater than 40%

Investigations have demonstrated that the rollover threshold for all vehicles especially heavy trucks is strongly influenced by the payload centre of gravity height. Ervin R.D. (1983) revealed that for heavy vehicles, the rollover threshold decreases by approximately 0.05g for each 25 cm (10 inch) increase in the payload centre of gravity height [8]. Cocosila M. (1996) cited about a study result conducted by the Bureau of Motor Carrier Safety of US Department of Transportation [40]. The agency recorded 9000 accidents involving various heavy commercial vehicles for the period of 1976 to 1979. It showed that fully loaded vehicles with rollover threshold of approximately 0.4g were almost ten times most likely to rollover as empty vehicles with rollover threshold of approximately 0.65g.

2.8 Basic Mathematical Model of Rollover Dynamics

Several roll models have been developed by the researchers around the world. Cameron J.T. (2005) found 23 unique vehicle models in different literatures that included a full mathematical description of roll dynamics [41]. Cocosila M. (1996) explained about the three-dimensional and two-dimensional theoretical modeling of rollover of heavy trucks [40]. As a concluding remark he noted that, three-dimensional model is closer to the real scenario. To avoid the complexity of mathematical parts, the three-dimensional models often neglect many influential factors such as suspension and tire non-linearities, type and dynamic position of loading, torsional compliances of frames etc. On the other hand, two-dimensional models are easy to investigate for their reduced degrees of freedom, though tire behavior, suspension or fifth wheel backlash are neglected.

2.8.1 Quasi-Static Rigid Body Model

The most fundamental model of rollover dynamics is the "Quasi-Static Rigid Body Model". Deflection of the suspension and tires is neglected in this model. Gillespie T.D. and Ervin R.D. (1983) illustrated the basic model [35]. The rollover process is demonstrated in Figure 2.2. In a steady state turning, a lateral force arising from

lateral acceleration acts at the centre of gravity and develops an overturning moment. The moment then tends to roll over the vehicle at outer tire contact point. To counter balance the overturning process a stabilizing moment is developed by the self-weight of the vehicle acting vertically downward through the centre of gravity. As long as the resultant of the two forces falls inside of the outer wheels, the vehicle is said to be stable in roll point of view. When the lateral acceleration is larger enough, the resultant force passes outside of the outer wheels that lead to cause overturning. At this point, the whole vehicle weight is transferred to the outer wheels i.e. the load on the inside wheels become zero.
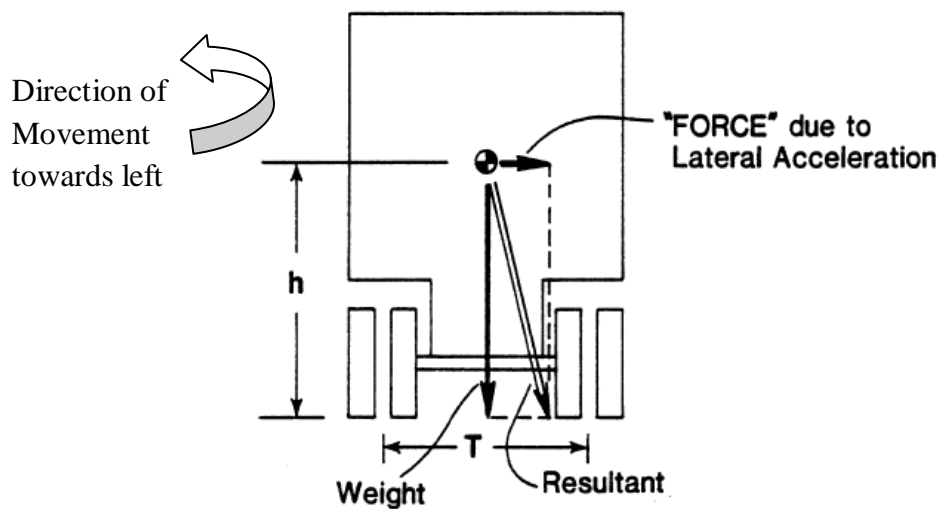
Figure 2.2: Rigid Vehicle Roll Model (Reference: Gillespie T.D. and Ervin R.D. (1983))

The figure represents a vehicle moving towards left. Taking moments about the outer tire i.e. right tire contact point,

M. a_y. h – M. g. T/2 = 0……………………..(i)

=> a_y/g = T/2h…………………….(ii)

The left side of the equation (ii) a_y/g is termed as Rollover Threshold.
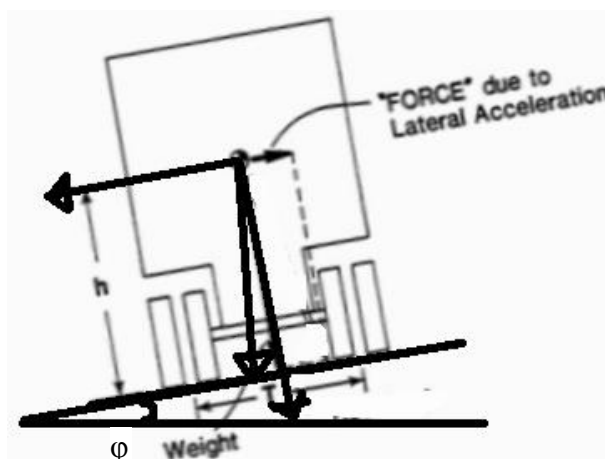
When cross-slope downward to the inside direction is considered, it helps to counterbalance the lateral acceleration. Cross slope angle (φ) is normally small and hence small

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angle approximation ($\sin \varphi = \varphi$ and $\cos \varphi = 1$) can be implemented here [36].

The left side of equation (i) is then,

$M. a_y. h - M.g.\cos \varphi. T/2 - M. g. \sin \varphi. h = 0$………………………..(iii)

$M. a_y. h - M.g. T/2 - M. g. \varphi. h = 0$ [As $\sin \varphi = \varphi$ and $\cos \varphi = 1$]

$\Rightarrow a_y/g = (T/2 + \varphi .h) / h$……………………(iv)

As roll angle builds up, the resisting moment produced by the vehicle's weight decreases as the centre of gravity is lifting and shifting towards the outer wheels. Figure 2.3 illustrates the relation between lateral acceleration and roll angle. At zero roll angle lateral acceleration can be any value up to rollover threshold. At this point, the inside wheels lift off the ground and the vehicle begins to roll. When the roll angle is increased to any value from zero, the lateral acceleration needed to roll over becomes less. Once the roll angle reaches at the value equal to arctan of T/2h, the centre of gravity is just over the outside wheels and the necessary lateral acceleration is zero. Beyond the points where $a_y=0$ and $\varphi=0$, any slight disturbance, that increases the roll angle, may cause the vehicle to overturn or any excess lateral acceleration produces roll acceleration that leads to rollover.
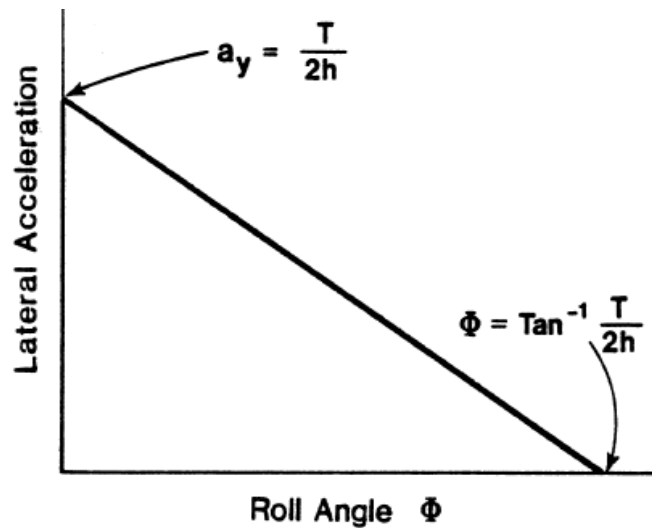
Figure 2.3: Lateral Acceleration Verses Roll Angle for Rigid Body Model
(Reference: Gillespie T.D. and Ervin R.D. (1983))

2.8.1 Quasi-Static Suspended Body Model

Tire and suspension compliances are considered in this model and assumed the total mass of the vehicle as sprung mass. Under the action of a lateral acceleration, the sprung mass rolls about an imaginary point called "roll center", placed at some distance above the road surface at the mid track position. The position of the roll centre is determined by the suspension geometry. Although this rolling motion of sprung mass is resisted by the roll stiffness of the suspension system, the lateral shift of the center of gravity places it closer to the outside wheel, thus reducing the lever arm available for the gravitational force resisting rollover. The following figure 2.4 illustrates rollover of a vehicle with suspension compliances.
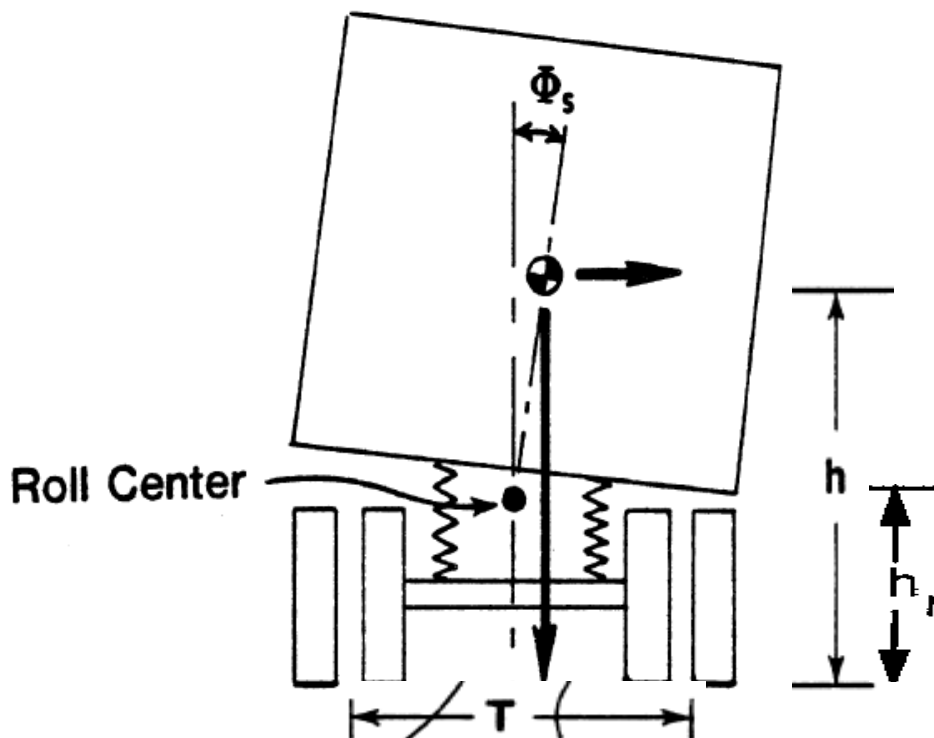
Figure 2.4: Roll Model of Suspended Vehicle (Reference: Gillespie T.D. and Ervin R.D. (1983))

Taking moments about the outer tire contact point,

$$M. a_y. h - M.g. [T/2 - (h - h_r). \tan \varphi] = 0 \dots\dots\dots\dots\dots\dots\dots..(v)$$

For small angle approximation, $\tan \varphi = \varphi$

Equation (v) can be expressed as

$$a_y/g = T/2h - (1 - h_r/h). \varphi \dots\dots\dots\dots\dots\dots\dots\dots..(vi)$$

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Thus, in suspended vehicle model, the rollover threshold is reduced by the second term of the right hand side of equation (vi). It is clearly seen that, the position of roll centre height influences the roll angle and thereby affects the rollover threshold. The rollover threshold with suspension compliance will always be less than that estimated for the rigid vehicle. The reduction will normally be in the range of 5 percent to 20 percent of the "rigid" model value, depending on the properties of the vehicle [9].

2.9 Overview

This chapter tries to summarize the research work carried out on run-off-road crashes and rollover of heavy vehicles in different countries. It also gives a brief discussion on safety research in Bangladesh. The following chapter outlines the methodology of this research work.

CHAPTER 3

METHODOLOGY AND DATA COLLECTION

3.1 Introduction

This chapter outlines a framework of developing a mathematical model for diagnosing run-off-road crashes in highways of Bangladesh. It also describes the road geometric and vehicular data for model calibration.

3.2 Methodological Steps

A systematic approach would be adopted to study the run off road crashes in highways of Bangladesh. The study involves data collection; data analysis using Micro Computer Accident Analysis Package (MAAP); analytical model development; selection of parameter values; model verification; model calibration; model validation; determination of critical overturning criteria and provision of some specific guidelines.

3.2.1 Data Collection

To achieve the first objective of this research as mentioned in chapter 1, crash data would be analyzed in MAAP5 software. In Bangladesh there are many sources for collecting road accident data e.g. police records, hospitals, insurance companies, news paper reporting etc. The basic source of accident data is the Accident Report Form (ARF), which is primarily filled up by police personnel. These ARF and MAAP soft copy are edited by the researchers in Accident Research Institute (ARI), BUET. All type of crash data needed for this study would be collected from ARI, BUET.

3.2.2 Data Analysis using MAAP5 Software

This section would discuss the characteristics and striking features of overall road traffic accidents and run-off-road accident on national highways in Bangladesh. Accident data would be analyzed for the period of 13 years, 1998-2010.

3.2.3 Analytical Model Development

Rollover of vehicles may not be the sole result of driver performance, rather it is due to the result of complex interaction among vehicle loading pattern, loading centre of

gravity height, tire characteristics, improper super elevation, cross slope, shoulder drop off, existence of pothole etc.

To attain the objectives from 2nd to 4th, a model would be developed which demonstrates the critical overturning criteria in terms of CG height, shoulder drop-off, pothole depth, speed and weight of vehicle assuming all other vehicle and road properties constant. The model would be based on 'Quasi-Static Rollover Model' of vehicle dynamics.

3.2.4   Verification of Model

Model verification is the process of error checking. It determines whether the logic, that describes the underlying mechanics of the model, is faithfully captured by the computer code and produces expected results or the logic is deviated. In this study, the model would be verified by writing codes in MS Excel 2007.

3.2.5   Selection of Parameter Values

As stated earlier in chapter 1, in terms of road geometric condition, vehicle modification, loading characteristics etc. Bangladesh is a country with some special peculiarities that differ a lot from the others. Hence the parameter values is different to some extent. The value of parameter such as roadway crowning, overall vehicle height, shoulder width, speed etc. would be so chosen that those should fall in the range of current practice and trend.

3.2.6   Model Calibration

Model calibration is the process of adjusting and modifying the default input parameter values so as to reflect the local study area's traffic conditions and behavior. For the purpose of model calibration site investigation would be done to accumulate the following real life data set.

- Cross sectional data of the roadway
- Speed Data
- Loading and Vehicle Data

3.2.7 Determination of Critical Overturning Criteria

The model would be run on MS Excel 2007 iteratively using different sets of parameter values and critical overturning criteria would be established.

3.2.8 Validation and Simulation

Simulation would be done using SimuLink tool in MATLAB. The Simscape tool of SimuLink provides built-in vehicle dynamics (mechanical) functions. As lateral dynamics is not included in this tool, user defined block library would be created using Simscape language to include lateral dynamics.

3.2.9 Recommendation of Some Specific Guidelines

Some specific guidelines for overloading height, shoulder drop off, loading pattern etc. would be recommended to reduce the run-off-road incident.

3.3 Data Collection for Model Calibration

To calibrate the model, the default input parameter values are to be so chosen that they satisfy local study area's traffic conditions and behavior. For gathering various vehicle related data, Batholi Axle Load Control Station is selected. This station is 53 km from Dhaka and on the Dhaka-Manikganj section of National Highway N5. For road geometry related data, 1 km road segment is investigated near Batholi Bazar.

Model calibration process requires the following parameters to be collected:

- Cross sectional data of road geometry (shoulder drop-off, width of soft/hard shoulder etc.)
- Speed data
- Loading and vehicle data
- Overall Vehicle Data

3.3.1 Cross Sectional Data of Road Geometry

Lane and shoulder width, shoulder drop-off on both segments is collected using 'Measuring Wheel' and 'Tape'. The average lane width is 10.5 ft. Shoulder consists

of paved hard shoulder of about 5 ft and unpaved earthen soft shoulder with 3 ft width. The edge of paved shoulder is somewhere damaged due to rutting of soft shoulder and results in a drop-off of about 2.5 in to as high as 9.25 in. The typical condition of lane-shoulder is shown in Figure 4.1to 4.5.

Figure 3.1: Typical Lane and Shoulder

Figure 3.2: Shoulder Damage due to Rutting of Soft Soil

Drop-off is about 9.25 inch due to soft shoulder rutting

Figure 3.3: Height of Drop-off
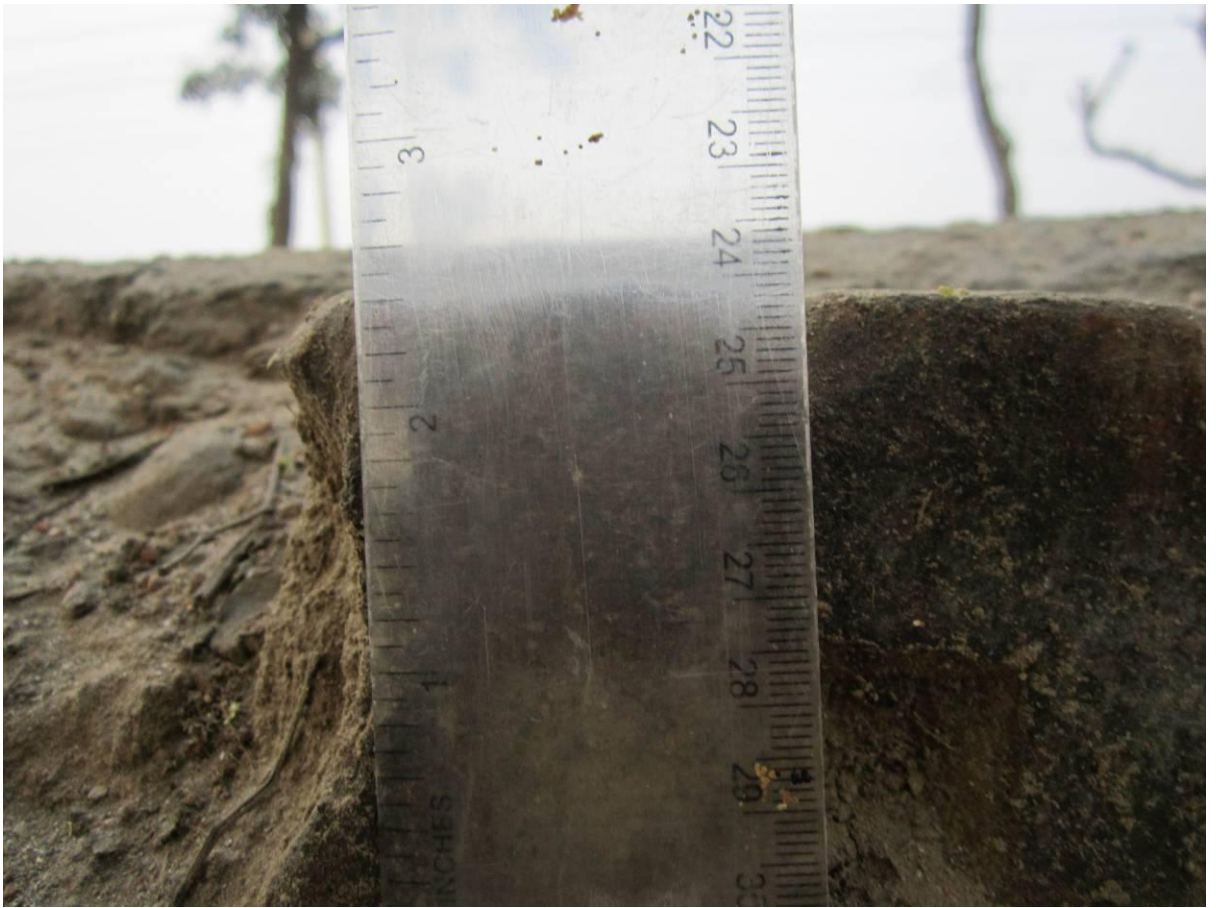
Figure 3.4: 2.5 inch Drop-off

**Figure 3.5: Overtaking of Opposing Vehicle Forces Left Lane Bus
to Encroach on to Shoulder**

3.3.2 Speed Data

Speed data is collected randomly using 'Speed Radar Gun'. The average speed of truck observed is 40 km/h.

3.3.3 Loading and Vehicle Data

Vehicle loading (weight) is measured using ground weigh machine with a helping hand from the Axle Load Control Station Authority. Carrier height along with the overall height of vehicle is measured using 'Tape'. Track width is also measured at this stage. Photographs are taken using digital camera for the assessment of bulging shape and size. Model number of the vehicles is also be amassed. All the data is shown in Table 3.1 below.

Figure 3.6 illustrates bulging of loading on a truck. More photographs are shown in Appendix II.

Figure 3.6: Bulging of Loading

Table 3.1: Samples of Axle Loading and other Vehicular Data

SL No.	Model No.	Track Width (ft)	Wheel Base (ft)	Carrier Height (ft)	Loading Height above Carrier (ft)	Height of Truck Bed from Ground (ft)	Total Height (ft)	Gross Vehicle Weight (lb)	Front Axle		Rear Axle		Loading Extension (in)	Width of Load Bulging (in)
									Weight (lb)	% of GVW	Weight (lb)	% of GVW		
1	Tata 1612	6.08	9.74	4	5.17	4.58	13.75	31900	9900	31.03	22000	68.97	0	0
2	Tata 1612	6.08	9.02	4	4.17	4.67	12.84	41360	9460	22.87	31900	77.13	0	0
3	Tata 1613	6.08	9.28	4.33	3.5	4.58	12.41	29040	8140	28.03	20900	71.97	0	0
4	Tata 1613	6.08	15.65	4.67	3.66	4.08	12.41	40920	12320	30.11	28600	69.89	0	0
5	----	6.08	16.44	4.83	4.08	4.08	12.99	73480	18480	25.15	55000	74.85	0	0
6	Eicher 2016 (Covered Van)	6	15.45	8.42	---	3.71	12.13	41580	13200	31.75	28380	68.25	0	0
7	Eicher 2016	6	14.34	4.25	6.25	4.67	15.17	30140	10340	34.31	19800	65.69	0	0
8	Hino	6	15.91	4.25	5.5	4.58	14.33	30140	10340	34.31	19800	65.69	0	0

From the table it is seen that the highest Gross Vehicle Weight (GVW) is 73480 lb (33.4 ton) and maximum overall vehicle height is 15.17 ft. According to the station authority, maximum allowable GVW is 44000 lb (20 ton) and about 30% trucks are overloaded. The maximum weight they found is as high as 103400 lb (47 ton). When asked about overall height they told that they never measure it before. But they can guess that sometimes the overall height may be as high as 17 ft.

Figure 3.7: Truck Containing Timber Log Weighing 73480 lb (33.4 ton)

Figure 3.8: Heavy Truck with Overall Height 15.17 ft

3.3.4 Limitations of Data Collection

Data is collected during daytime from 9:00 am to 4:00 pm. The frequency of truck movement in the axle load station increases particularly at night. Therefore, collected data is few in number though the tabulation is representative.

3.4 Overview

The chapter summarizes the systematic approaches which would be adopted to study single vehicle run-off-road crashes in highways of Bangladesh. It also describes the data collection process and presents the collected data.

CHAPTER 4

DATA ANALYSIS AND MODEL DEVELOPMENT

4.1 Introduction

This chapter is divided into two portions. The first section presents detailed systematic analysis of collected crash data. Five years of accident data (2006-2010) is analyzed using Microcomputer Accident Analysis Package (MAAP5) software to find out the general characteristics of run-off-road accident. The second portion describes the most important and significant part of this research work i.e. systematic model development process. The model development portion is further sub-divided in six sections. The motivation behind model development comes first. In the second section, assumptions of the model are presented. The third section elaborates the whole model. The fourth and fifth section deals with the verification and calibration process. Detail analysis with the model is demonstrated in the last section.

4.2 Analysis of Crash Data

The analysis involves the determination of accident and severity characteristics according to the variables listed below:

- Environmental characteristics:
  - Year, month of year, day of week and time of day;
  - Light conditions (i.e. day, night, dusk or dawn);
  - Road conditions (wet or dry);
  - Weather conditions (raining, clear etc);

- Road related characteristics:
  - Type of junctions (i.e. cross, tee, staggered etc.);
  - Road geometry (straight, curve etc.);
  - Road surface quality (smooth, rough etc.);
  - Road class (national, regional etc.);
  - Road feature (bridge, culvert etc.);
  - Road location (urban, rural);
  - Highway route (national highway 1, 2,… etc.);

- Vehicle related characteristics:
  - Vehicle type;
  - Vehicle loading;

- Vehicle defects;
- Vehicle damage;

- Driver related characteristics:
    - Driver age;
    - Driver injury;
    - Drink driving;
    - Driving with/without seat belts;

- Passenger related characteristics:
    - Passenger age;
    - Passenger injury;
    - Passenger sex;
    - Passenger position in vehicle;

- Contributing factor related characteristics;

4.2.1   Accident and Severity Scenario

Prior to analysis of run-off-road (ROR) accident, total accident and severity scenario of different types of accident is analyzed using 13 years of crash data 1998-2010. Table 4.1 and Figure 4.1 to 4.3 illustrate in detail.

Table 4.1: Distribution of Accidents by Severity from 1998-2010

	Accident						Casualty					
	Fatal	Grievous	Simple	Collision	Total	% of Total	Fatal	Grievous Injury	Simple injury	Total	% of Total Fatality	Fatality Index
Head-On	4259	1779	442	240	**6720**	14.66	11385	4857	1074	**17316**	22.17	1.69
Rear-End	3633	1982	462	850	**6927**	15.11	6239	3609	786	**10634**	12.15	0.90
Right-angle	193	170	23	121	**507**	1.11	368	346	43	**757**	0.72	0.73
Side-swipe	1409	684	263	359	**2715**	5.92	2684	1386	511	**4581**	5.23	0.99
Overturn	2790	791	273	33	**3887**	8.48	7659	2739	829	**11227**	14.91	1.97
Hit Object 1	228	77	31	81	**417**	0.91	442	151	80	**673**	0.86	1.06
Hit Object 2	588	234	125	175	**1122**	2.45	1435	712	280	**2427**	2.79	1.28
Hit Park Vehicle	553	245	87	163	**1048**	2.29	1130	551	178	**1859**	2.20	1.08
Hit Pedestrian	16885	3475	428	0	**20788**	45.36	18383	3929	501	**22813**	35.79	0.88
Hit Animal	15	5	0	7	**27**	0.06	22	21	0	**43**	0.04	0.81
Other	1212	321	82	58	**1673**	3.65	1610	492	136	**2238**	3.13	0.96
Total	**31765**	**9763**	**2216**	**2087**	**45831**	**100**	**51357**	**18793**	**4418**	**74568**	**100**	**1.12**
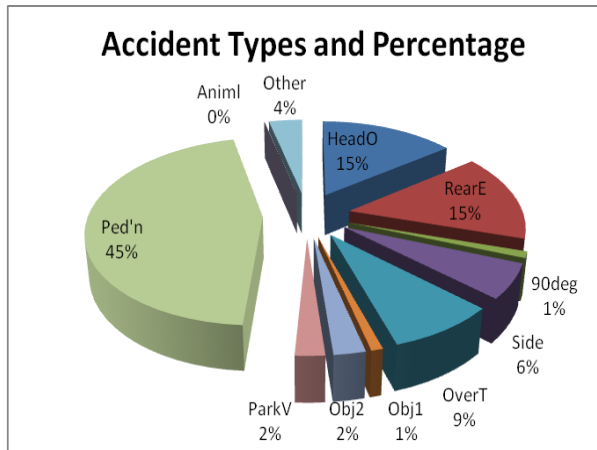
Figure 4.1: Percentage of different Types of Accident
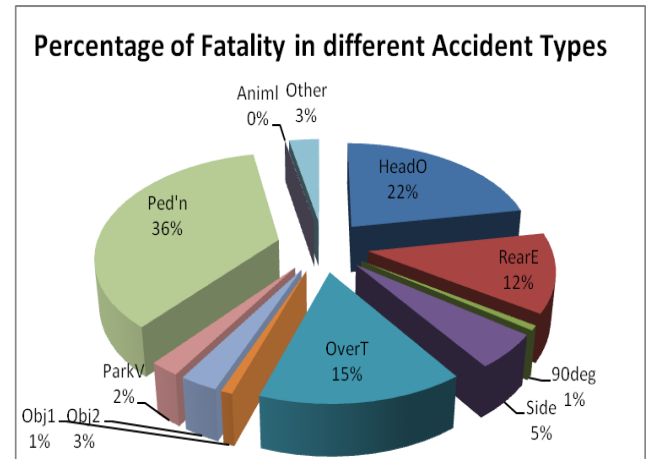
Figure 4.2: Percentage of Fatality in different Types of Accident
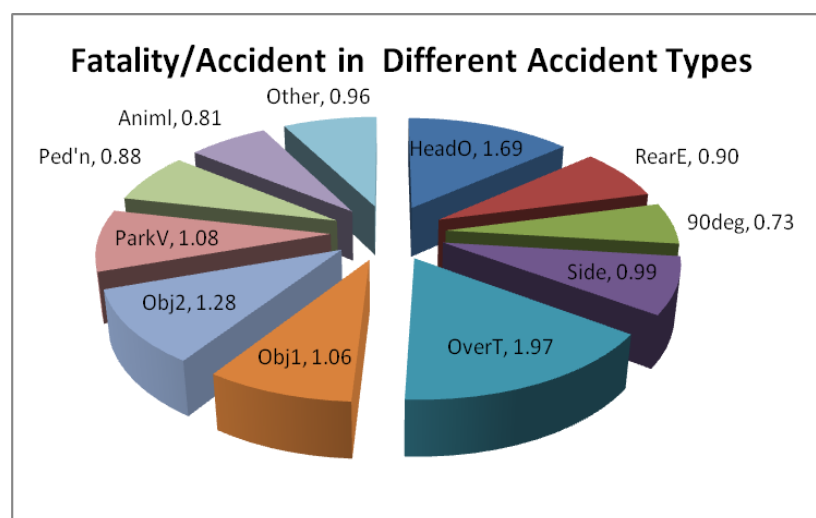
Figure 4.3: Fatality/Accident in different Types of Accident

Figure 4.1 and Figure 4.2 show the percentage of accidents and corresponding fatalities in various accident types. It is seen that pedestrian accident (45%) occurs most but fatality is comparatively low (35%). Though the head on (15%) and rear end accident (15%) is of same percentage, fatality in head on (22%) is more severe than that in rear end (12%). The most interesting is that, though the percentage of overturning accident is much less than that of others, its consequences is more alarming. Only 9% accidents result in 15% fatality. Figure 4.3 explains more showing a pie chart of fatality/accident, known as fatality index. It is clear that, overturning accident with fatality index 1.97 and head on accident with 1.69 are the most dominant accident types.

Running off road may occur in any of these accidents as an aftermath. As stated earlier, these accidents are categorized into ten groups of accident types, coded from 0

to 9 according to the Road User Movement (RUM) code. Based on the direction of run off, the accident type 7 and 8 is coded into 700, 701, 702 … 707 and 800, 801….805 as shown in Appendix I. In this thesis, the overturning accidents on which a vehicle leaves off the road are referred to as single vehicle run-off-road accidents. 705 is overturned on road; 706 and 707 is off carriageway turning in intersection and account for less than 2% overturning accident. Type 8 is on curve road. These types are excluded in the analysis. Only type 701-704 is considered for the rest of the analysis. The striking features of the analysis are presented in Appendix III.

4.3 Model Development

Analysis of crash data shows that, overturning of vehicles to the left or right of carriageway on straight or curved road comprises about half of the Run-off-Road (ROR) crashes in Bangladesh. According to the Accident Report Form (ARF), excessive speeding and reckless driving (both are related to driver's behavior) are the prime causes of rollover type ROR crashes. In reality, these two are the general causal factors behind every road accident. As the accident reporting system in Bangladesh as well as the ARF is lacking specific geometry and vehicle related data, it necessitates ROR crashes to be analyzed and investigated thoroughly.

Rollover of vehicles may not be the sole result of driver performance, rather it is due to the result of complex interaction among vehicle loading pattern, tire characteristics, improper super elevation, cross slope, shoulder drop off, vehicle speed etc.

Vehicles with high centre of gravity (CG) are more prone to rollover accident. The lower the position of CG the lesser is the chance to overturn. The location of CG of a vehicle largely depends on the loading pattern. Heavily loaded vehicles with high height usually have higher CG. While the vehicle is in motion, due to the loosely fitted loading pattern, jerking, and vibration effect from the potholes and rough road surface, the horizontal position of CG gradually shifts towards the direction of roadway slope. Both the height and horizontal shifting of CG make a vehicle more prone to overturn.

Shoulder drop off is another factor to rollover. It is the vertical elevation difference between two adjacent roadway surfaces. Edge drop-offs are potential safety hazards

because significant vertical differences between surfaces can reduce vehicle stability and impede a driver's ability to handle a vehicle. This height difference imposes hazards to vehicles resulting in overturning on shoulders. When left wheels go onto the shoulder, the drop-off causes load difference between left and right tires. In effect, the resultant moment increases due to tilting of vehicles.

Vehicle speed and overloading condition are the other factors that may affect the stability of vehicles.

Considering all these facts, in this research work, an analytical model has been developed which relates these factors with ROR crash. Though ROR crashes involving buses result more fatalities and casualties, considering importance of freight transportation, in this study a model is developed for heavy truck.

4.3.1 Assumptions

For the model development purpose, some assumptions are made as follows:
- The roadway is assumed to be straight road segment with a dry surface which provides sufficient friction for traction.
- Though the crowning of road is provided in parabolic shape at the time of construction, for simplification of calculation it is assumed to be straight.
- The vehicle is assumed to be heavy truck without any defect.
- Bulging of loading will occur for loose-fitting loading and due to continuous jerking and vibration.
- As the bulging pattern is unconfined, for calculation purpose semi-parabolic and parabolic spandrel is assumed.
- Though the road segment is considered as straight, in order to express the effect of lane changing behavior (when the vehicle is trying to re-enter the roadway) steering angle at front wheel is included in the model.

4.3.2 Derivation of the Model

The model is based on the 'Quasi-Static Rollover Model'; a fundamental model in vehicle dynamics. As stated earlier in the chapter of literature review, this quasi-static

model deals with rollover threshold while the vehicle is in a steady state turn. According to the model, rollover threshold is a function of the 'Track Width' and the 'Center of Gravity Height' in the case of 'Rigid Vehicle'. If the vehicle is suspended, the 'Track Width', the 'Center of Gravity Height', the 'Roll Centre Height' and the 'Roll Angle' yield the rollover threshold.

To determine and quantify the effect of 'Shoulder Drop-off' with/without pothole on it and the effect of 'Bulging of Loading' on rollover threshold, some extra parameters are included in the model. The model also establishes the 'Critical Overturning Criteria'. A model is developed based on Rigid Vehicle Model.

Let us assume that a heavy truck is moving forward on the left lane. At any instant of movement, the driver of the truck rotates the steering to the left to avoid any surprised situation, to give way to overtaking vehicle, or to avoid side friction from the opposing vehicles. This situation is illustrated in Figure 4.4 as position (1). For that, the front left wheel encroaches onto the shoulder [position (2)]. At this moment, the driver abruptly rotates the steering to the right to re-enter to its original path [black color front wheel in position (2)]. Meanwhile the rear left wheel also goes on shoulder [position (3)].

At position (3), lateral acceleration develops due to the cornering forces and it acts in the opposite direction of turning (in this case to the left).

Figure 4.4: Schematic Diagram of Vehicle Leaving off and Returning to Roadway

The rear view of position (3) is shown on Figure 4.5. The Figure illustrates all the forces and reactions. It is assumed that there is a shoulder drop-off and pothole exists on the shoulder.

4.3.3 Rigid Vehicle Model

Rigid vehicle means that suspension and tire deflection is neglected in the analysis. According to the Figure 4.5, the cross slope angle with horizontal is α and shoulder slope angle with horizontal is β. The centre of gravity of the body is designated as CG'. Though initially the centre of gravity lies at the mid of the loading width, for bulging of loading, it is shifted x' distance towards left from the mid-track position.
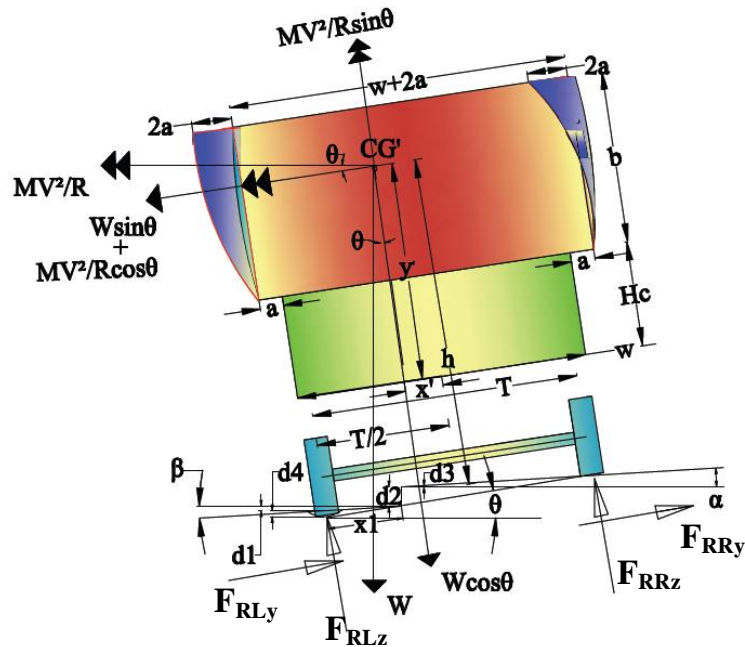
Figure 4.5: Forces and Reactions of a Heavy Truck in Rigid Vehicle Model

The description of the symbols used in this Figure is given below.

α	= Pavement cross slope angle with horizontal
β	= Slope angle of shoulder with horizontal
θ	= Inclination Angle (Angle between roll plane with horizontal)
M	= Mass of the vehicle
V	= Speed of the vehicle
R	= Radius of turn
d_1	= Vertical distance of shoulder plane from the horizontal plane
d_2	= Shoulder drop-off
d_3	= Vertical distance between horizontal plane and road surface
d_4	= Depth of pothole on shoulder

x_1 = Distance from pavement edge to centre of Rear-left tire

h = Centre of gravity height on level ground

T = Wheel Track

MV^2/R = Lateral force acting through CG at right angles to vehicle body

W = Weight of the vehicle acting downward through CG

F_{RLy}, F_{RLz} = Reactions due to rear left wheel load

F_{RRy}, F_{RRz} = Reaction due to rear right wheel load

The weight of the truck acts vertically downward through the CG. The weight and the lateral force are divided along and vertical to the roll plane (the plane connecting left and right wheels). Taking moment at contact point of left tire, we get,

$[W. \cos \theta – (MV^2/R). \sin \theta]. (T/2 - x') - F_{RRz}.T - [W. \sin \theta + (MV^2/R). \cos \theta]. h = 0$ ....(4.1)

Where,

$h_{cg} = y'_{total}$ [y' = CG Height of loaded truck on level ground]
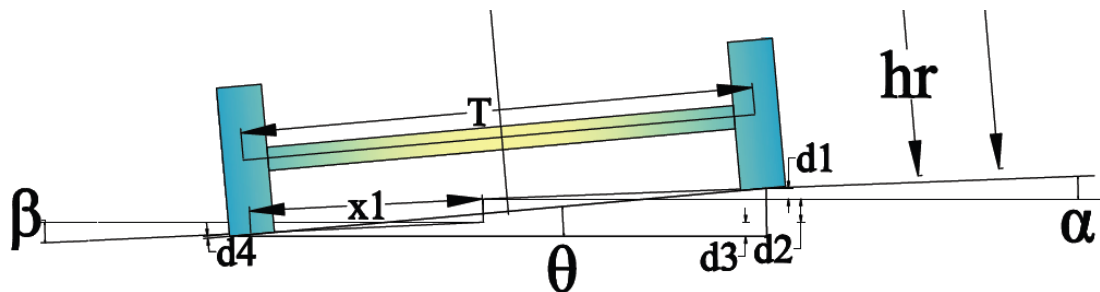
Figure 4.6: Calculation of Inclination Angle

$\sin\theta$ $= (d_1 + d_2 + d_3 + d_4) / T$

$\sin\theta$ $= [(T – x_1) \sin\alpha + d_2 + x_1 \sin\beta + d_4] / T$

θ $= \sin^{-1}[((T – x_1) \sin \alpha + x_1 \sin\beta + d_2 + d_4) / T]$

At the instant when overturning is about to occur, $F_{RRz} = 0$, equation (4.1) can be written as,

$[W. \cos \theta – (MV^2/R). \sin \theta]. (T/2 - x') - [W. \sin \theta + (MV^2/R). \cos \theta]. h = 0$

$\Rightarrow [Mg. \cos \theta – (Ma_y). \sin \theta]. (T/2 - x') - [Mg. \sin \theta + (Ma_y). \cos \theta]. h = 0$ [As V^2/R is the lateral acceleration]

$\Rightarrow g. \cos \theta. (T/2 - x') - g. \sin \theta. h = a_y. \sin \theta. (T/2 - x') + a_y. \cos \theta. h$

$\Rightarrow a_y /g = [\cos \theta. (T/2 - x') – h. \sin \theta] / [\sin \theta. (T/2 - x') + h. \cos \theta]$

Dividing both side by $\cos \theta$ yields

$a_y /g = [T/2 - x' – h. \tan \theta] / [h + (T/2 - x'). \tan \theta]$ ……………….(4.2)

The term a_y is the lateral acceleration in g's and usually known as the 'Rollover Threshold'. This equation establishes the critical overturning criteria.

Implication of Critical Overturning Criteria:

- Comparing with rollover threshold of quasi-static rigid body model, the numerator of equation (4.2) clearly shows that it is less than T/2; at the same time, the denominator indicates that it is of larger value than h. Therefore the rollover threshold of this very model is obviously has a lower value which indicates higher probability of overturning.

- The larger the inclination angle, which is positively related to shoulder drop-off, the lesser is the value of rollover threshold.

- The greater the horizontal shift of centre of gravity, the lesser is the value of rollover threshold.

Theoretically, rollover occurs when Overturning Moment, M_O > Stabilizing Moment, M_S. Little change in inclination angle, cg height or horizontal shift of cg from the equilibrium state may lead to a rollover.

From Figure 4.5,

Overturning Moment, M_O $\quad = [W. \sin \theta + (MV^2/R). \cos \theta]. h$

Stabilizing Moment, M_S $\quad = [W. \cos \theta - (MV^2/R). \sin \theta]. (T/2 - x')$

In the section of "Analysis of Model", more will be discussed and illustrated with example.

4.3.4 Verification of the Model

Model verification is the process of error checking. It determines whether the logic, that describes the underlying mechanics of the model, is faithfully captured by the computer code and produces expected results or the logic is deviated. In this study, the model is verified by writing codes in MS Excel 2007.

For the verification, random values of the model parameters are entered into the code and corresponding results of calculation are carefully investigated in every step. Errors, found in the calculation, have been corrected in every iterative step.

4.3.5 Selection of Input Parameter Values

In terms of road geometric condition, vehicle modification, loading characteristics etc. Bangladesh is a country with some special peculiarities that differ a lot from the others. Hence, the parameter values would be different to some extent. The value of parameter such as roadway crowning, overall vehicle height, shoulder width, speed etc. would be so chosen that those should fall in the range of current practice and trend.

- Roadway crowning is assumed to be 3% i.e. cross slope angle, $\alpha = 1.72$ degrees
- Shoulder slope is assumed to be 5% i.e. shoulder slope angle, $\beta = 2.86$ degrees
- Overall height of vehicle is included as variable with values 12 ft (3.65 m) to 17 ft (5.2 m) considering Bangladeshi practice.
- Wheel track, width of vehicle and wheelbase is selected as per standard dimension (Baseline Vehicle is TATA LPT 1613).
- Carrier height is chosen as 4 ft (1.2 m).
- To determine the value of radius of turn of the wheels, steering angle at front wheel is assumed to be 5°.
- Six types of loading condition are chosen for the model; one for standard vehicle with GVW 35640 lb (16.2 ton) and five others are overloaded vehicle with GVW 44000, 55000, 66000, 77000 and 88000 lb (20, 25, 30, 35 and 40 ton respectively).
- Speed is chosen as 20 ft/s (22 km/h), 25 ft/s (27.5 km/h) and 30 ft/s (33 km/h).

4.3.6 Calibration of the Model

Model calibration is the process of adjusting and modifying the default input parameter values so that they reflect the local study area's traffic conditions and behavior. For the purpose of model calibration, site investigation has been done to accumulate real life data set.

4.3.7   Analysis of the Model

Throughout the analysis, rigid vehicle model is used. For the analysis purpose, let us assume a heavy truck of width w, carrier height H_c and track width T as illustrated in Figure 4.7. The height of loading above the carrier is 'b'. The loading expands in both side of carrier with distance 'a' and hence the total loading width above carrier is w+2a. The centre of gravity lies at the mid of the loading width. When the bulging of loading occurs, the CG is shifted towards the direction of inclination. Figure 4.8 illustrates the bulging effect.
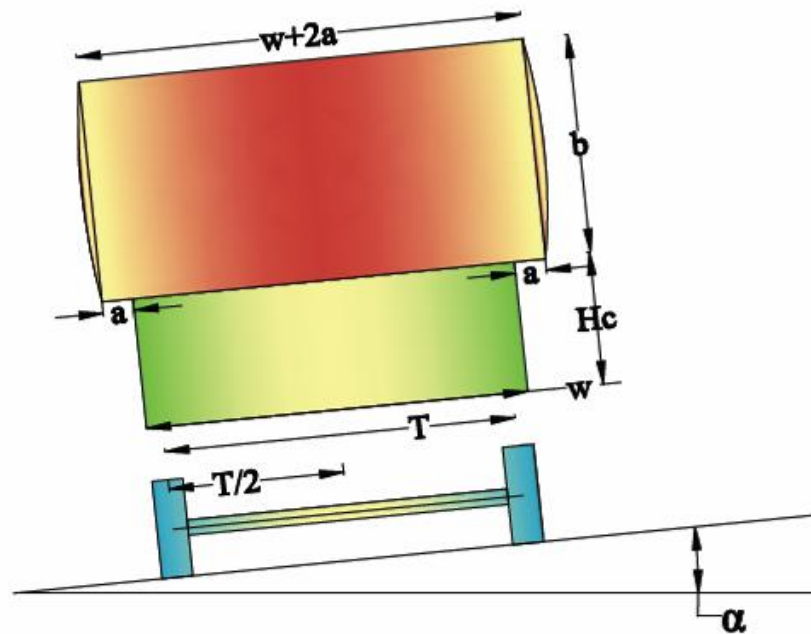
Figure 4.7: Schematic Diagram of a Heavy Truck on Inclined Road

Let us assume that for bulging, the left portion of loading is shifted '2a' distance towards left from previous position. It is denoted as 'A1' in the Figure 4.8. The right side of the loading is also moved '2a' towards left. It is denoted as 'A3'. For simplification of calculation, the side of the actual loading is assumed to be straight and after bulging, the shape is assumed to be semi parabolic. This bulging pattern is referred to as '2a bulging' throughout the calculation.
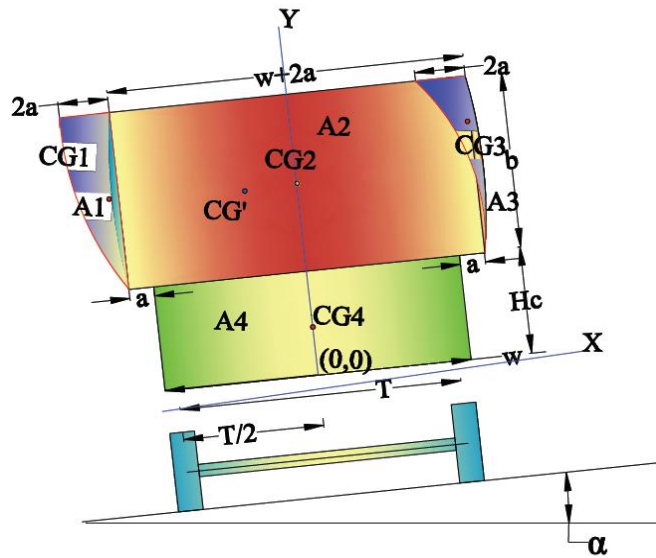
Figure 4.8: Bulging of Loading

The red dot in A1 represents the CG of that portion. Similarly, the yellow, red and red dot in A2, A3 and A4 respectively represents the corresponding CG of that portion. The CG of total loading is shown by blue dot and denoted as CG'. X and Y is the reference axis and the position of CG' is calculated from origin (0, 0). CG2 and CG4 stay on Y-axis.

CG Calculation of Loaded Truck

$$x'_{total} = (x'_{load} \cdot M_{load} + x'_{empty} \cdot M_{empty}) / M_{tot} = (x'_{load} \cdot M_{load} + 0) / M_{tot}$$

$$= x'_{load} \cdot (M_{tot} - M_{empty}) / M_{tot}$$

$$y'_{total} = (y'_{load} \cdot M_{load} + y'_{empty} \cdot M_{empty}) / M_{tot}$$

$$= (y'_{load} \cdot (M_{tot} - M_{empty}) + y'_{empty} \cdot M_{empty}) / M_{tot}$$

CG of empty truck along with other vehicles can be found from the chart below (Figure 4.9).

Vehicle Type	CG Height	Tread	Rollover Threshold
Sports car	18-20 inches	50-60 inches	1.2-1.7 g
Compact car	20-23	50-60	1.1-1.5
Luxury car	20-24	60-65	1.2-1.6
Pickup truck	30-35	65-70	0.9-1.1
Passenger van	30-40	65-70	0.8-1.1
Medium truck	45-55	65-75	0.6-0.8
Heavy truck	60-85	70-72	0.4-0.6

Figure 4.9: Chart of CG Height, Tread and Rollover Threshold of Vehicles (Reference: Gillespie T.D., "Fundamentals of Vehicle Dynamics", 1992)

$x'_{empty} = 0$ inch from mid line

$y'_{empty} = 70$ inch from road surface

CG of the loading body can be calculated using simple mechanics. The following section demonstrate the calculation steps for 2a bulging.

CG Calculation for '2a Bulging'

According to Figure 4.9,

$x_1 = -[w/2 + a + (2/5).2a] = -[w/2 + 9a/5]$

$y_1 = [H_c + 5b/8]$

$A_1 = (2/3).(2a).b = 4ab/3$

$x_2 = 0$

$y_2 = H_c + b/2$

$A_2 = (w + 2a)b$

$x_3 = [w/2 + a - (3/10).2a] = w/2 + 4a/10$

$y_3 = H_c + 3b/4$

$A_3 = (2a)(b/3) = 2ab/3$

$x_4 = 0$

$y_4 = H_c/2$

$A_4 = H_c w$

$x_1. A_1 = -[w/2 + 9a/5]. 4ab/3$

$x_2. A_2 = 0$

$x_3. A_3 = [w/2 + 4a/10]. 2ab/3$

$x_4. A_4 = 0$

$y_1. A_1 = [H_c + 5b/8]. 4ab/3$

$y_2. A_2 = [H_c + b/2]. (w + 2a).b$

$y_3. A_3 = [H_c + 3b/4]. 2ab/3$

$y_4. A_4 = (H_c/2).H_c w = H_c^2.w/2$

$A_1 + A_2 - A_3 + A_4 \quad = 4ab/3 + (w + 2a)b - 2ab/3 + H_c w$

$\qquad\qquad\qquad\quad = 8ab/3 + (H_c+b)w$

$x'_{load} = (x_1.A_1 + x_2.A_2 - x_3.A_3 + x_4.A_4) / (A_1 + A_2 - A_3 + A_4)$

$$= [-(w/2 + 9a/5).\ 4ab/3 + 0 - (w/2 + 4a/10).\ 2ab/3 + 0] / [8ab/3 + (H_c+b)w]$$

$$= - [(w/2 + 9a/5).\ 4ab/3 + (w/2 + 4a/10).\ 2ab/3] / [8ab/3 + (H_c+b)w]$$

The (-) sign of x'_{load} clearly represents the horizontal shifting of CG towards left.

$$y'_{load} = [\ y_1.A_1 + y_2.A_2 -\ y_3.A_3 + y_4.A_4] / [A_1 + A_2 - A_3 + A_4]$$
$$= [(H_c + 5b/8).\ 4ab/3 + (H_c + b/2).\ (w + 2a)b - (H_c + 3b/4).\ 2ab/3 + H_c^2.w/2] / [8ab/3 + (H_c+b)w]$$

4.3.8   Analysis for '2a Bulging'

To determine whether the vehicle overturns or not and to get the value of rollover threshold, calculations are performed in MS Excel 2007. Figure 4.10 illustrates the calculation steps. According to the Figure, the orange color cells are the main input variables. To determine the change of rollover threshold with the change of these input variables is the main purpose of this analysis. The pink colored cell is the value of rollover threshold. When the difference between overturning moment and stabilizing moment is positive this threshold value indicates rollover threshold. The yellow marked cell is the radius of turn of wheels. This value is calculated using 'Cornering Equation' of vehicle dynamics for a given values of gross weight and speed.

$$\delta = 57.3(L/R) + (W_f/C_{\alpha f} - W_r/C_{\alpha r}) * V^2/Rg \quad ………………(4.3)$$
where,

δ = Steering angle at the front wheels (deg)

W_f = Load on front axle (lb)

W_r = Load on rear axle (lb)

$C_{\alpha f}$ = Cornering stiffness of the front tires (lb/deg)

$C_{\alpha r}$ = Cornering stiffness of the rear tires (lb/deg)

L = Wheel base (ft)

R = Radius of turn (ft)

V = Vehicle speed (fps)

g = Gravitational acceleration (32.2 f/s^2)

w (ft)	H_c (ft)	b (ft)	T (ft)	a (inch)	d_2 (inch)	d_4 (inch)	x_1 (ft)	M_{tot} (kg)	V (ft/s)	R (ft)	M_{Empty} (kg)
8	4	8.5	6	3	2.5	0	4	40000	24	88.31	4595

Loading CG	x'_{load} =	2.09148265	inch to left from mid line
	y'_{load} =	76.28706625	inch from truck bed
Empty Truck CG	x'_{empty} =	0	inch to left from mid line
	y'_{empty} =	60	inch from road surface
Loaded Truck CG	x'_{total} =	1.85122358	inch to left from mid line
	y'_{total} =	122.21	inch from level ground
Loaded Truck CG from Roll Plane	$h = y'_{total}$ =	122.21	inch
Overall Vehicle Height		17	ft
Inclination Angle	θ =	0.078070349	radian (4.47 Degrees)
Overturning Moment	M_O =	3.0E+06	in-lb
Stabilizing Moment	M_S =	2.9E+06	in-lb
Difference between Moment	$M_O - M_S$ =	62196.58114	in-lb **Rollover Occur**

Lateral Acceleration needed for Rollover			Lateral Acc. Of the Vehicle by g		Rollover Threshold on Level Ground	
Rollover Threshold	a_y/g =	0.197	V^2/Rg	0.203	T/2h =	0.295

Figure 4.10: Calculation Steps for 2a Bulging in MS Excel 2007

To find the appropriate value of cornering stiffness of front and rear tire, which is needed for determining radius of turn, standard graph of cornering stiffness by normal load is used considering the extensiveness of vehicle weighing pattern in Bangladesh.
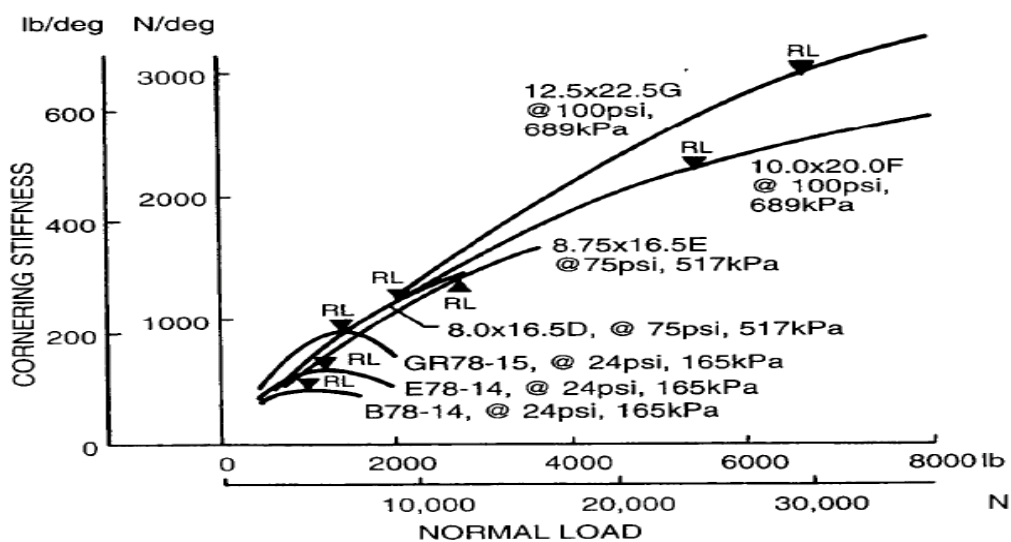
Figure 4.11: Standard Graph of Cornering Stiffness Verses Normal Load

Figure 4.11 illustrates the standard graph of cornering stiffness by normal load. It is clearly understood from this Figure that maximum load is only 8000 lb. But in Bangladesh heavy trucks are carrying weight as much as 99000 lb (45 ton) or over. Average weight distribution between front (15% on each) and rear tires (17.5% on each) confirms that normal load on rear tire might be of 17325 lb or more. Therefore equation 4.4 is used to find out the value of cornering stiffness.

$$C = A_0 + A_1 F_n - (A_1/A_2)F_n^2 \ \ldots\ldots(4.4)$$

Where,

C = Cornering Stiffness

A_0, A_1, and A_2 are constants

F_n = Normal Load

For roadway crowning, left tires undergo more load than right. The tire loads are calculated using the following formula illustrated by Figure 4.11.
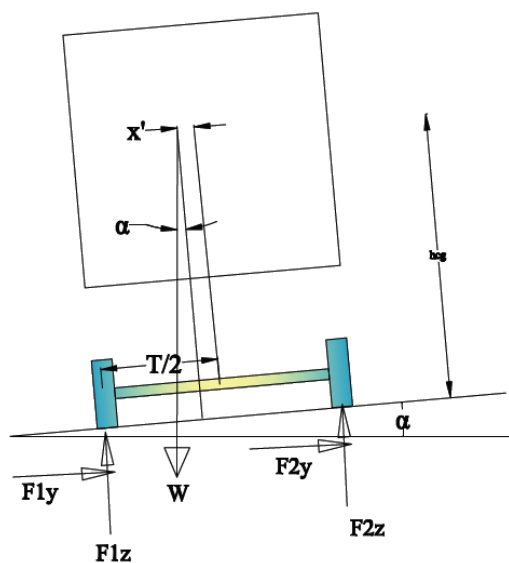
Figure 4.12: Reactions of Tires due to
Road Crowning

According to the Figure, the load on rear axles (70% of total) is supported by the tire reactions F_{1z} and F_{2z}. Taking moment at left tire contact point yields,

$$F_{2z}.T - W\cos\alpha(T/2 - x') + W\sin\alpha.h_{cg} = 0$$

$$F_{2z} = W[\cos\alpha\,(T/2 - x') - h_{cg}.\sin\alpha] / T$$

Similarly,

$$F_{1z} = W[\cos\alpha(T/2 + x') + h_{cg}.\sin\alpha] / T$$

Throughout the analysis, this wheel reaction i.e. tire loading is used as tire normal load for calculating cornering stiffness.

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At the time of re-entering to road from shoulder, centripetal force acts leftward through CG as the vehicle is in cornering to right as shown in Figure 4.12. The vertical difference between left and right tires makes an inclination angle θ.

Reactions for Cornering to Right on Staraight Road (Combined Front and Rear)

Figure 4.13: Reactions of Tires due to Cornering to Right
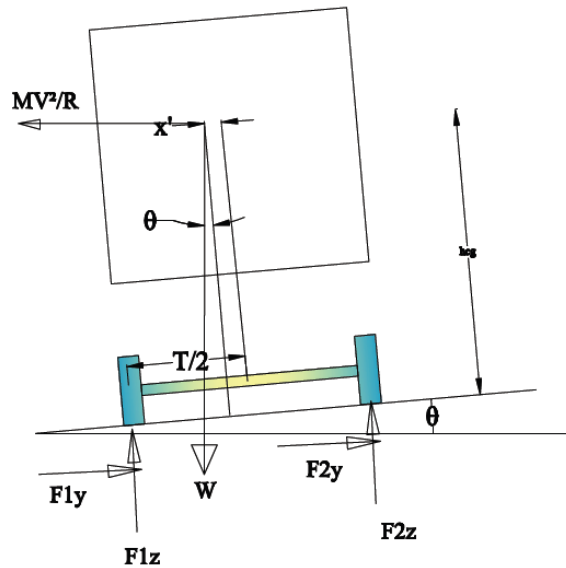
Taking moment about left contact point yields,

F_{2z} = [W(cosθ(T/2 − x') - h_{cg}. sinθ) − MV^2/R(sinθ(T/2 − x') + h_{cg}. cosθ)] / T

Throughout the analysis, this reaction i.e. right tire load is used for calculating stabilizing moment at cornering to right.

At first, certain speed is so chosen that the difference between steering angle (δ) and front slip angle (α_f) is positive. Using equation 4.3 radius of turn (R) is calculated in excel sheet as shown in Table 4.2.

Table 4.2: Calculation of Radius of Turn

Steering Angle, δ (deg)	Wheel Base, L (ft)	Tire Nomal Load, F_{zf} (lb)	Tire Nomal Load, F_{zr} (lb)	Front Cornering Stiffness, C_{af} (lb/deg)	Rear Cornering Stiffness, C_{ar} (lb/deg)	Forward Velocity, V (ft/s)	Radius of Turn, R (ft)	Front Slip Angle, α_f (deg)	Rear Slip Angle, α_f (deg)	δ - α_f
5	16	5758	6717	507.20	556.98	25	137.36	1.5	3.2	3.5

This speed (V) and corresponding radius of turn (R) are then set in equation for a given value of gross vehicle weight. Then the value of loading extension 'a' is put in an incremental order of 1 inch from 0 to 6 inch. At this stage, rollover threshold is obtained for overall height of 12 -17 ft at every increase in drop-offs of 0.5 inch until rollover occurs. These critical values are kept in tabular format as shown in Table 4.3.

Table 4.3: Critical Overturning Criteria for Different Loading Conditions

	Critical Overturning Criteria																							
	Gross Vehicle Weight 16.2 Ton				Gross Vehicle Weight (16.3-20 Ton)				Gross Vehicle Weight (21-25 Ton)				Gross Vehicle Weight (26-30 Ton)				Gross Vehicle Weight (31-35 Ton)				Gross Vehicle Weight (36-40 Ton)			
	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g
a = 0 inch	12	20	19	0.077	12	20	18.5	0.076	12	20	17.5	0.083	12	20	17	0.086	12	20	16.5	0.090	12	20	15.5	0.103
		25	15	0.135		25	14	0.141		25	13	0.149		25	12	0.159		25	10	0.185		25	7	0.227
		30	8	0.238		30	6.5	0.252		30	4	0.282		30	1	0.323		------	------	------		------	------	------
	13	20	18	0.075	13	20	17	0.080	13	20	16.5	0.081	13	20	16	0.083	13	20	15	0.093	13	20	14.5	0.099
		25	13.5	0.140		25	12.5	0.146		25	11.5	0.153		25	10.5	0.163		25	8.5	0.189		25	6	0.223
		30	7	0.235		30	5.5	0.248		30	3	0.278		30	0	0.319		------	------	------		------	------	------
	14	20	17	0.074	14	20	16	0.079	14	20	15.5	0.079	14	20	14.5	0.089	14	20	14	0.093	14	20	13.5	0.097
		25	12.5	0.139		25	11.5	0.144		25	10.5	0.151		25	9	0.168		25	7.5	0.186		25	4.5	0.228
		30	6	0.234		30	4.5	0.247		30	2	0.276		30	0	0.301		------	------	------		------	------	------
	15	20	16	0.074	15	20	15	0.079	15	20	14	0.085	15	20	13.5	0.088	15	20	13	0.092	15	20	12.5	0.097
		25	11.5	0.139		25	10.5	0.144		25	9.5	0.151		25	8	0.168		25	6.5	0.186		25	3.5	0.227
		30	5	0.234		30	3	0.254		30	0.5	0.281		30	0	0.285		------	------	------		------	------	------
	16	20	15	0.076	16	20	14	0.080	16	20	13	0.084	16	20	12.5	0.088	16	20	12	0.093	16	20	11	0.103
		25	10.5	0.141		25	9.5	0.145		25	8.5	0.152		25	7	0.168		25	5.5	0.186		25	2.5	0.227
		30	4	0.235		30	2.5	0.247		30	0	0.276		30	0	0.271		------	------	------		------	------	------
	17	20	14	0.078	17	20	13.5	0.075	17	20	12.5	0.082	17	20	12	0.084	17	20	11	0.094	17	20	10.5	0.099
		25	10	0.135		25	9	0.140		25	7.5	0.153		25	6	0.168		25	4.5	0.188		25	1.5	0.229
		30	3	0.237		30	1.5	0.249		30	0	0.263		30	0	0.257		------	------	------		------	------	------

Table 4.3: Continued

		Gross Vehicle Weight 16.2 Ton				Gross Vehicle Weight (16.3-20 Ton)				Gross Vehicle Weight (21-25 Ton)				Gross Vehicle Weight (26-30 Ton)				Gross Vehicle Weight (31-35 Ton)				Gross Vehicle Weight (36-40 Ton)			
		Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g
a = 1 inch		12	20	18.5	0.080	12	20	18	0.078	12	20	17.5	0.079	12	20	16.5	0.089	12	20	16	0.093	12	20	15	0.103
			25	14.5	0.138		25	13.5	0.144		25	12.5	0.152		25	11	0.167		25	9.5	0.187		25	6.5	0.228
			30	8	0.233		30	6.5	0.247		30	4	0.277		30	0.5	0.325		30	------	------		30	------	------
		13	20	17.5	0.077	13	20	17	0.076	13	20	16	0.083	13	20	15.5	0.085	13	20	15	0.089	13	20	14	0.101
			25	13.5	0.136		25	12.5	0.141		25	11	0.155		25	10	0.165		25	8	0.189		25	5	0.230
			30	7	0.231		30	5	0.251		30	2.5	0.280		30	0	0.313		30	------	------		30	------	------
		14	20	16.5	0.076	14	20	15.5	0.082	14	20	15	0.081	14	20	14.5	0.083	14	20	13.5	0.094	14	20	12.5	0.103
			25	12.5	0.134		25	11.5	0.139		25	10	0.153		25	9	0.163		25	7	0.188		25	4	0.229
			30	5.5	0.237		30	4	0.249		30	1.5	0.278		30	0	0.295		30	------	------		30	------	------
		15	20	15.5	0.077	15	20	14.5	0.081	15	20	14	0.081	15	20	13	0.089	15	20	12.5	0.094	15	20	11.5	0.103
			25	11.5	0.134		25	10.5	0.139		25	9	0.153		25	7.5	0.168		25	6	0.187		25	3	0.228
			30	4.5	0.236		30	3	0.248		30	0	0.281		30	0	0.279		30	------	------		30	------	------
		16	20	14.5	0.078	16	20	13.5	0.081	16	20	13	0.082	16	20	12.5	0.084	16	20	11.5	0.094	16	20	10.5	0.104
			25	10.5	0.136		25	9.5	0.140		25	8	0.153		25	6.5	0.168		25	5	0.188		25	2	0.229
			30	4	0.230		30	2	0.249		30	0	0.270		30	0	0.265		30	------	------		30	------	------
		17	20	13.5	0.080	17	20	13	0.077	17	20	12	0.084	17	20	11.5	0.086	17	20	10.5	0.095	17	20	10	0.101
			25	9.5	0.138		25	8.5	0.142		25	7	0.155		25	6	0.164		25	4	0.189		25	1	0.230
			30	3	0.232		30	1	0.251		30	0	0.257		30	0	0.252		30	------	------		30	------	------

Table 4.3: Continued

	Critical Overturning Criteria																								
	Gross Vehicle Weight 16.2 Ton				Gross Vehicle Weight (16.3-20 Ton)				Gross Vehicle Weight (21-25 Ton)				Gross Vehicle Weight (26-30 Ton)				Gross Vehicle Weight (31-35 Ton)				Gross Vehicle Weight (36-40 Ton)			
	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g
a = 2 inch	12	20	18.5	0.075	12	20	17.5	0.081	12	20	17	0.081	12	20	16.5	0.084	12	20	15.5	0.094	12	20	15	0.100
		25	14	0.140		25	13.5	0.140		25	12	0.154		25	11	0.164		25	9	0.190		25	6	0.230
		30	7.5	0.236		30	6	0.250		30	3.5	0.279		30	0	0.328		------	------	------		------	------	------
	13	20	17	0.080	13	20	16.5	0.078	13	20	15.5	0.085	13	20	15	0.087	13	20	14.5	0.091	13	20	13.5	0.103
		25	13	0.138		25	12	0.143		25	11	0.150		25	9.5	0.167		25	8	0.185		25	4.5	0.232
		30	6.5	0.233		30	5	0.246		30	2	0.281		30	0	0.307		------	------	------		------	------	------
	14	20	16	0.079	14	20	15.5	0.077	14	20	14.5	0.083	14	20	14	0.085	14	20	13	0.094	14	20	12.5	0.101
		25	12	0.137		25	11	0.142		25	9.5	0.154		25	8.5	0.165		25	6.5	0.190		25	3.5	0.231
		30	5.5	0.232		30	4	0.244		30	1	0.280		30	0	0.290		------	------	------		------	------	------
	15	20	15	0.079	15	20	14.5	0.076	15	20	13.5	0.083	15	20	13	0.085	15	20	12	0.094	15	20	11.5	0.100
		25	11	0.137		25	10	0.141		25	8.5	0.155		25	7.5	0.164		25	5.5	0.188		25	2.5	0.230
		30	4.5	0.231		30	2.5	0.250		30	0	0.279		30	0	0.274		------	------	------		------	------	------
	16	20	14	0.080	16	20	13.5	0.077	16	20	12.5	0.084	16	20	12	0.085	16	20	11	0.095	16	20	10.5	0.101
		25	10	0.138		25	9	0.142		25	8	0.148		25	6.5	0.164		25	4.5	0.189		25	1	0.236
		30	3.5	0.232		30	1.5	0.251		30	0	0.265		30	0	0.259		------	------	------		------	------	------
	17	20	13.5	0.075	17	20	12.5	0.079	17	20	11.5	0.084	17	20	11	0.087	17	20	10.5	0.091	17	20	9.5	0.102
		25	9	0.140		25	8	0.144		25	7	0.150		25	5.5	0.166		25	3.5	0.191		25	0	0.237
		30	2.5	0.234		30	0.5	0.251		30	0	0.251		30	0	0.246		------	------	------		------	------	------

	Critical Overturning Criteria																							
	Gross Vehicle Weight 16.2 Ton				Gross Vehicle Weight (16.3-20 Ton)				Gross Vehicle Weight (21-25 Ton)				Gross Vehicle Weight (26-30 Ton)				Gross Vehicle Weight (31-35 Ton)				Gross Vehicle Weight (36-40 Ton)			
	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g
a = 3 inch	12	20	18	0.078	12	20	17.5	0.077	12	20	16.5	0.084	12	20	16	0.086	12	20	15.5	0.090	12	20	14.5	0.102
		25	14	0.137		25	13	0.142		25	12	0.149		25	10.5	0.166		25	9	0.185		25	5.5	0.232
		30	7.5	0.232		30	6	0.245		30	3.5	0.274		30	0	0.322		------	------	------		------	------	------
	13	20	17	0.075	13	20	16	0.080	13	20	15.5	0.080	13	20	14.5	0.088	13	20	14	0.093	13	20	13	0.104
		25	13	0.133		25	11.5	0.146		25	10.5	0.152		25	9.5	0.162		25	7.5	0.187		25	4	0.234
		30	6	0.236		30	4.5	0.248		30	2	0.277		30	0	0.302		------	------	------		------	------	------
	14	20	16	0.074	14	20	15	0.079	14	20	14.5	0.078	14	20	13.5	0.087	14	20	13	0.091	14	20	12	0.102
		25	11.5	0.139		25	10.5	0.144		25	9.5	0.150		25	8	0.166		25	6	0.190		25	3	0.233
		30	5	0.234		30	3.5	0.246		30	1	0.274		30	0	0.284		------	------	------		------	------	------
	15	20	15	0.074	15	20	14	0.078	15	20	13	0.085	15	20	12.5	0.086	15	20	12	0.090	15	20	11	0.102
		25	10.5	0.139		25	9.5	0.143		25	8.5	0.149		25	7	0.165		25	5	0.190		25	1.5	0.239
		30	4	0.233		30	2.5	0.245		30	0	0.273		30	0	0.268		------	------	------		------	------	------
	16	20	14	0.075	16	20	13	0.079	16	20	12	0.084	16	20	11.5	0.087	16	20	11	0.091	16	20	10	0.102
		25	9.5	0.140		25	8.5	0.144		25	7.5	0.150		25	6	0.166		25	4	0.191		25	0.5	0.239
		30	3	0.234		30	1.5	0.245		30	0	0.259		30	0	0.253		------	------	------		------	------	------
	17	20	13	0.077	17	20	12	0.081	17	20	11.5	0.080	17	20	10.5	0.089	17	20	10	0.092	17	20	9	0.104
		25	9	0.135		25	7.5	0.144		25	6.5	0.151		25	5	0.168		25	3.1	0.191		25	0	0.233
		30	2.5	0.229		30	0.5	0.247		30	0	0.246		30	0	0.240		------	------	------		------	------	------

Table 4.3: Continued

	Critical Overturning Criteria																							
	Gross Vehicle Weight 16.2 Ton				Gross Vehicle Weight (16.3-20 Ton)				Gross Vehicle Weight (21-25 Ton)				Gross Vehicle Weight (26-30 Ton)				Gross Vehicle Weight (31-35 Ton)				Gross Vehicle Weight (36-40 Ton)			
	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g
a = 4 inch	12	20	18	0.074	12	20	17	0.079	12	20	16.5	0.079	12	20	15.5	0.089	12	20	15	0.093	12	20	14	0.105
		25	13.5	0.140		25	12.5	0.145		25	11.5	0.152		25	10	0.168		25	8.5	0.187		25	5	0.235
		30	7	0.235		30	5.5	0.247		30	3	0.277		30		0.317		------	------	------		------	------	------
	13	20	16.5	0.078	13	20	16	0.076	13	20	15	0.082	13	20	14.5	0.084	13	20	14	0.088	13	20	13	0.100
		25	12.5	0.136		25	11.5	0.141		25	10	0.154		25	9	0.164		25	7	0.189		25	3.5	0.237
		30	6	0.231		30	4	0.250		30	1.5	0.279		30		0.296		------	------	------		------	------	------
	14	20	15.5	0.076	14	20	14.5	0.081	14	20	14	0.080	14	20	13	0.089	14	20	12.5	0.092	14	20	11.5	0.104
		25	11.5	0.134		25	10.5	0.138		25	9	0.152		25	7.5	0.168		25	6	0.186		25	2.5	0.234
		30	5	0.229		30	3	0.248		30	0.5	0.276		30		0.278		------	------	------		------	------	------
	15	20	14.5	0.076	15	20	13.5	0.080	15	20	13	0.079	15	20	12	0.088	15	20	11.5	0.091	15	20	10.5	0.103
		25	10.5	0.134		25	9	0.145		25	8	0.151		25	6.5	0.167		25	4.5	0.192		25	1	0.240
		30	4	0.228		30	2	0.247		30	0	0.268		30		0.262		------	------	------		------	------	------
	16	20	13.5	0.077	16	20	12.5	0.081	16	20	12	0.080	16	20	11	0.089	16	20	10.5	0.092	16	20	9.5	0.104
		25	9.5	0.135		25	8.5	0.139		25	7	0.151		25	5.5	0.167		25	3.5	0.192		25	0	0.240
		30	3	0.229		30	1	0.247		30	0	0.253		30		0.247		------	------	------		------	------	------
	17	20	12.5	0.080	17	20	12	0.076	17	20	11	0.082	17	20	10.5	0.083	17	20	9.5	0.094	17	20	8.5	0.105
		25	8.5	0.137		25	7.5	0.140		25	6	0.153		25	5	0.162		25	3	0.187		25	0	0.227
		30	2	0.231		30	0	0.249		30	0	0.240		30		0.234		------	------	------		------	------	------

Table 4.3: Continued

	Gross Vehicle Weight 16.2 Ton				Gross Vehicle Weight (16.3-20 Ton)				Gross Vehicle Weight (21-25 Ton)				Gross Vehicle Weight (26-30 Ton)				Gross Vehicle Weight (31-35 Ton)				Gross Vehicle Weight (36-40 Ton)			
Critical Overturning Criteria																								
a	Overall Height (ft)	Speed (ft/s)	d₂ (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d₂ (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d₂ (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d₂ (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d₂ (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d₂ (inch)	a_y/g
a = 5 inch	12	20	17.5	0.077	12	20	16.5	0.082	12	20	16	0.082	12	20	15.5	0.084	12	20	14.5	0.095	12	20	14	0.099
		25	13.5	0.135		25	12.5	0.140		25	11	0.154		25	10	0.163		25	8	0.189		25	4.5	0.237
		30	7	0.230		30	5	0.250		30	2.5	0.279		30	0	0.311		------	------	------		------	------	------
	13	20	16.5	0.073	13	20	15.5	0.078	13	20	14.5	0.084	13	20	14	0.086	13	20	13.5	0.090	13	20	12.5	0.101
		25	12	0.138		25	11	0.143		25	10	0.149		25	8.5	0.165		25	6.5	0.191		25	3	0.239
		30	5.5	0.233		30	4	0.245		30	1.5	0.273		30	0	0.290		------	------	------		------	------	------
	14	20	15	0.079	14	20	14.5	0.076	14	20	13.5	0.082	14	20	13	0.083	14	20	12	0.094	14	20	11	0.106
		25	11	0.136		25	10	0.140		25	8.5	0.153		25	7.5	0.162		25	5.5	0.187		25	1.5	0.243
		30	4.5	0.231		30	2.5	0.250		30	0	0.278		30	0	0.272		------	------	------		------	------	------
	15	20	14	0.078	15	20	13.5	0.075	15	20	12.5	0.081	15	20	12	0.083	15	20	11	0.093	15	20	10	0.104
		25	10	0.136		25	9	0.140		25	7.5	0.153		25	6	0.168		25	4	0.193		25	0.5	0.242
		30	3.5	0.230		30	1.5	0.249		30	0	0.262		30	0	0.256		------	------	------		------	------	------
	16	20	13	0.080	16	20	12.5	0.076	16	20	11.5	0.082	16	20	11	0.083	16	20	10	0.094	16	20	9	0.105
		25	9	0.137		25	8	0.140		25	6.5	0.153		25	5.5	0.162		25	3	0.194		25	0	0.235
		30	2.5	0.231		30	1	0.242		30	0	0.247		30	0	0.242		------	------	------		------	------	------
	17	20	12.5	0.075	17	20	11.5	0.078	17	20	10.5	0.084	17	20	10	0.085	17	20	9	0.095	17	20	8	0.107
		25	8	0.139		25	7	0.142		25	6	0.148		25	4.5	0.163		25	2.5	0.188		25	0	0.222
		30	1.5	0.233		30	0	0.244		30	0	0.234		30	0	0.229		------	------	------		------	------	------

Table 4.3: Continued

	Critical Overturning Criteria																								
	Gross Vehicle Weight 16.2 Ton				Gross Vehicle Weight (16.3-20 Ton)				Gross Vehicle Weight (21-25 Ton)				Gross Vehicle Weight (26-30 Ton)				Gross Vehicle Weight (31-35 Ton)				Gross Vehicle Weight (36-40 Ton)			
	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g	Overall Height (ft)	Speed (ft/s)	d_2 (inch)	a_y/g
a = 6 inch	12	20	17	0.080	12	20	16.5	0.077	12	20	15.5	0.084	12	20	15	0.086	12	20	14.5	0.090	12	20	13.5	0.101
		25	13	0.138		25	12	0.142		25	11	0.149		25	9.5	0.165		25	7.5	0.191		25	4	0.239
		30	6.5	0.233		30	5	0.245		30	2.5	0.274		30	0	0.306		------	------	------		------	------	------
	13	20	16	0.076	13	20	15	0.080	13	20	14.5	0.079	13	20	13.5	0.088	13	20	13	0.091	13	20	12	0.103
		25	12	0.133		25	10.5	0.145		25	9.5	0.151		25	8	0.167		25	6	0.192		25	2.5	0.240
		30	5.5	0.228		30	3.5	0.247		30	1	0.275		30	0	0.285		------	------	------		------	------	------
	14	20	15	0.074	14	20	14	0.078	14	20	13	0.083	14	20	12.5	0.085	14	20	11.5	0.096	14	20	10.5	0.107
		25	10.5	0.139		25	9.5	0.142		25	8.5	0.148		25	7	0.164		25	5	0.189		25	1	0.244
		30	4	0.233		30	2.5	0.244		30	0	0.272		30	0	0.266		------	------	------		------	------	------
	15	20	14	0.073	15	20	13	0.077	15	20	12	0.083	15	20	11.5	0.084	15	20	10.5	0.094	15	20	9.5	0.106
		25	9.5	0.138		25	8.5	0.141		25	7	0.154		25	6	0.163		25	4	0.188		25	0	0.243
		30	3	0.232		30	1.5	0.243		30	0	0.256		30	0	0.250		------	------	------		------	------	------
	16	20	13	0.074	16	20	12	0.078	16	20	11	0.083	16	20	10.5	0.085	16	20	9.5	0.095	16	20	8.5	0.106
		25	8.5	0.139		25	7.5	0.142		25	6.5	0.147		25	5	0.163		25	2.5	0.195		25	0	0.229
		30	2.5	0.226		30	0.5	0.244		30	0	0.242		30	0	0.236		------	------	------		------	------	------
	17	20	12	0.077	17	20	11	0.080	17	20	10.5	0.078	17	20	9.5	0.087	17	20	9	0.090	17	20	7.5	0.108
		25	8	0.134		25	6.5	0.144		25	5.5	0.149		25	4	0.165		25	2	0.190		25	0	0.216
		30	1.5	0.228		30	0	0.238		30	0	0.229		30	0	0.223		------	------	------		------	------	------

4.3.9 Observations on the Result of Analysis

Figure 4.14 (a), (b), (c) and (d) illustrate the effect of vehicle weight, height and loading combinations with load bulging and extension on critical shoulder drop-off. It is clear from the figure that,

- The critical shoulder drop-off for which rollover occurs usually reduces with increase in vehicle weight, height, speed and load bulging.
- At 20 ft/s speed, the critical shoulder drop-off line gradually decreases with increase in vehicle weight.
- At 25 ft/s speed, the critical shoulder drop-off for which rollover occurs reduces abruptly with GVW more than 30 ton.
- The slope of the critical shoulder drop-off line is more steeper at 30 ft/s speed.
- The more the speed and weight the more is the chances to roll over.
- Low speed-high height combination and high speed-low height combination produce almost same result i.e. same value of critical shoulder drop-off upto GVW not more than 30 ton. For GVW more than 30 ton, the effect of speed is more prominent than that of height.
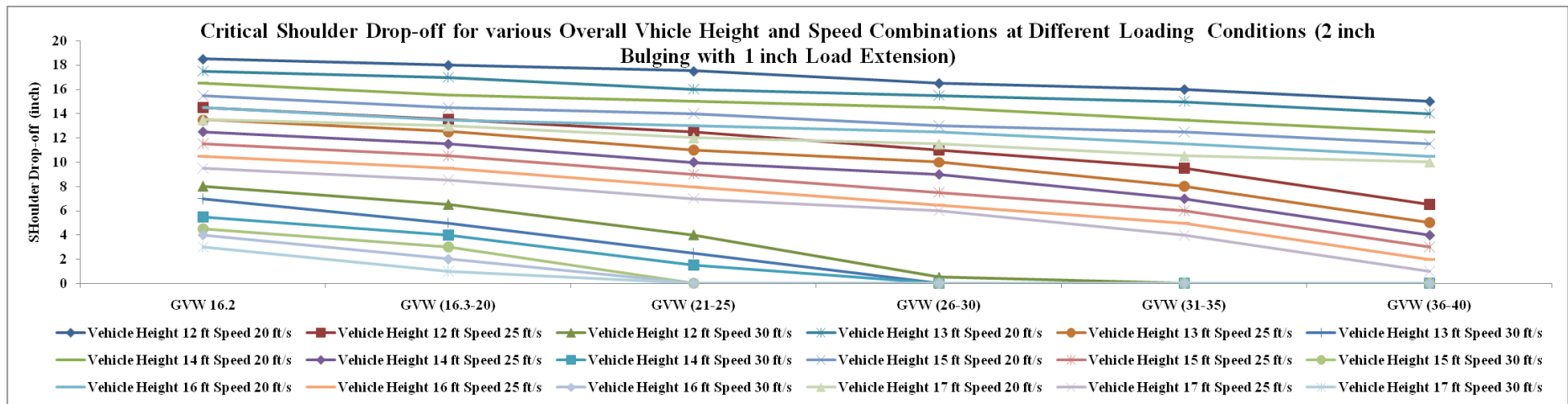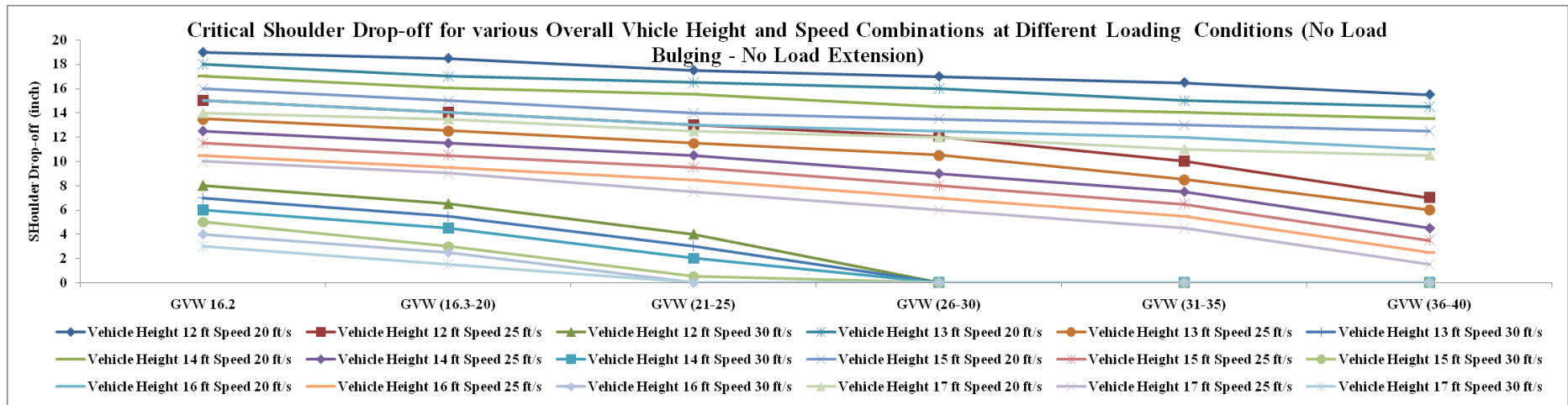
Figure 4.14 (a): Changes in Critical Shoulder Drop-off in Various Speed, Height and Loading Combinations with Load Bulging
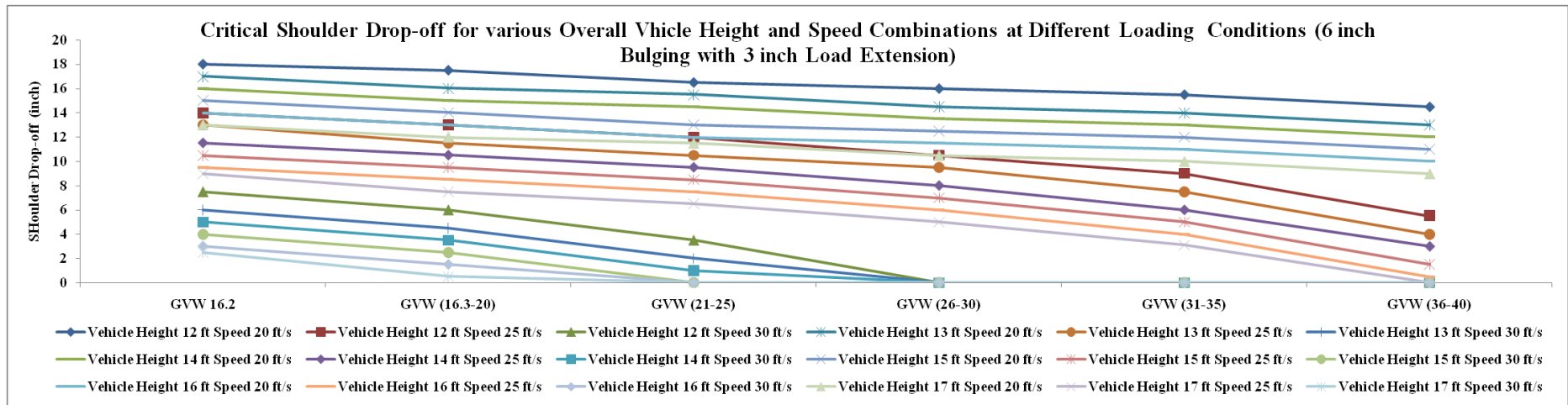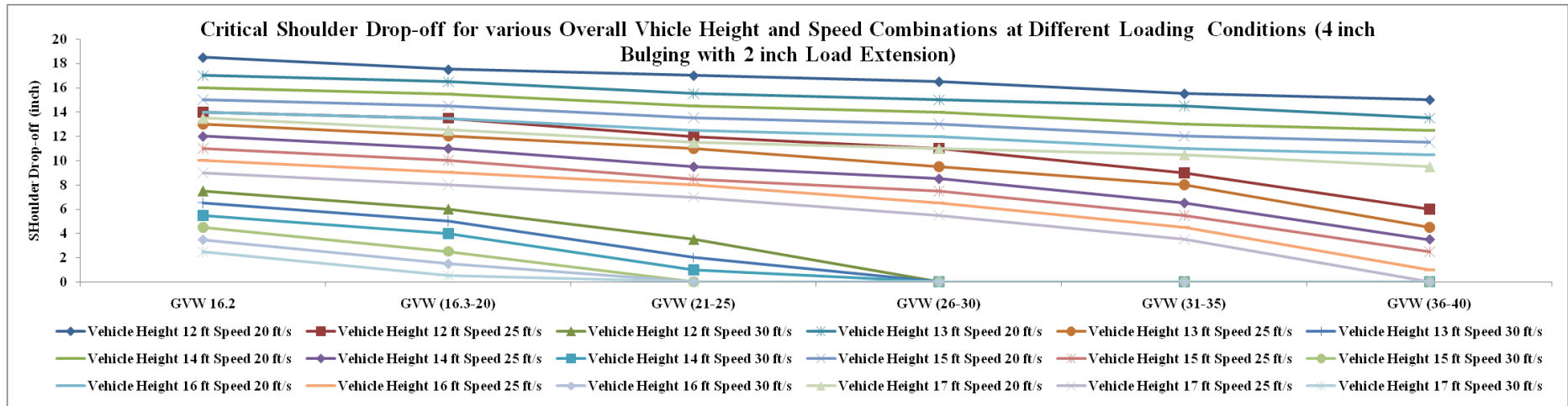
Figure 4.14 (b): Changes in Critical Shoulder Drop-off in Various Speed, Height and Loading Combinations with Load Bulging
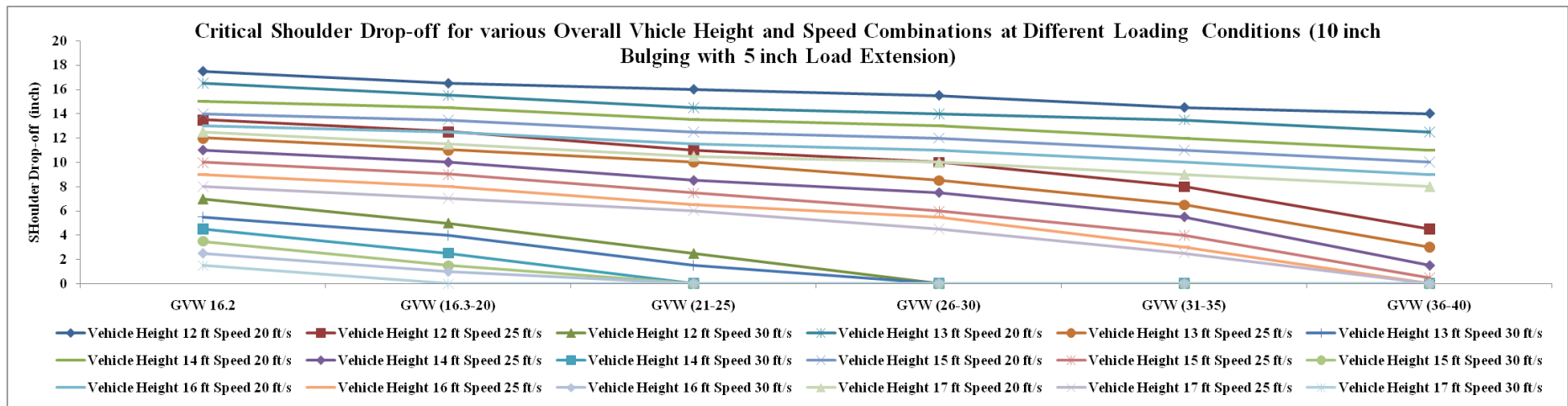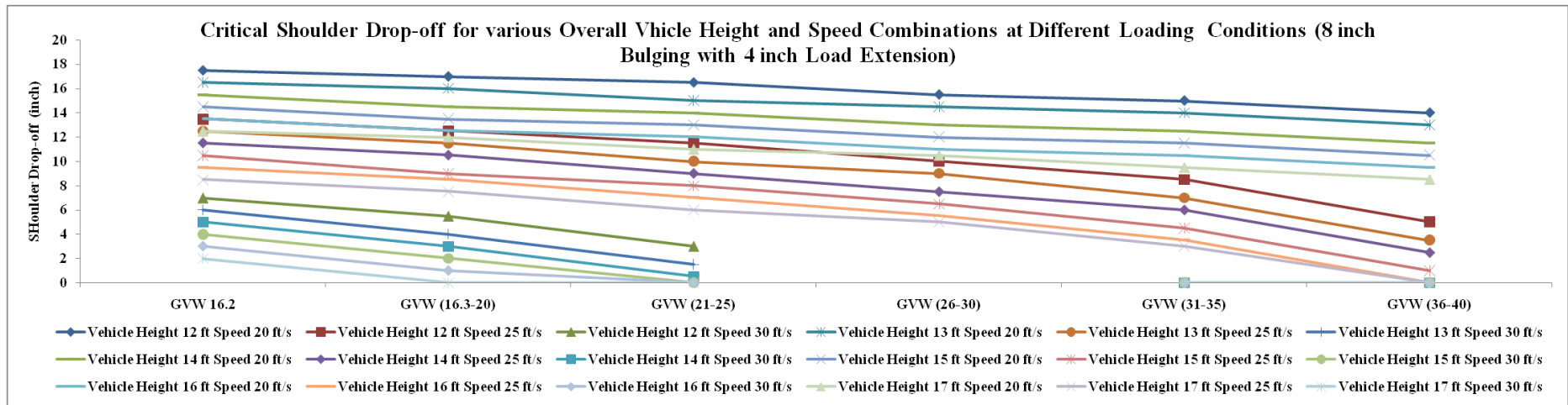
Figure 4.14 (c): Changes in Critical Shoulder Drop-off in Various Speed, Height and Loading Combinations with Load Bulging

Figure 4.14 (d): Changes in Critical Shoulder Drop-off in Various Speed, Height and Loading Combinations with Load Bulging
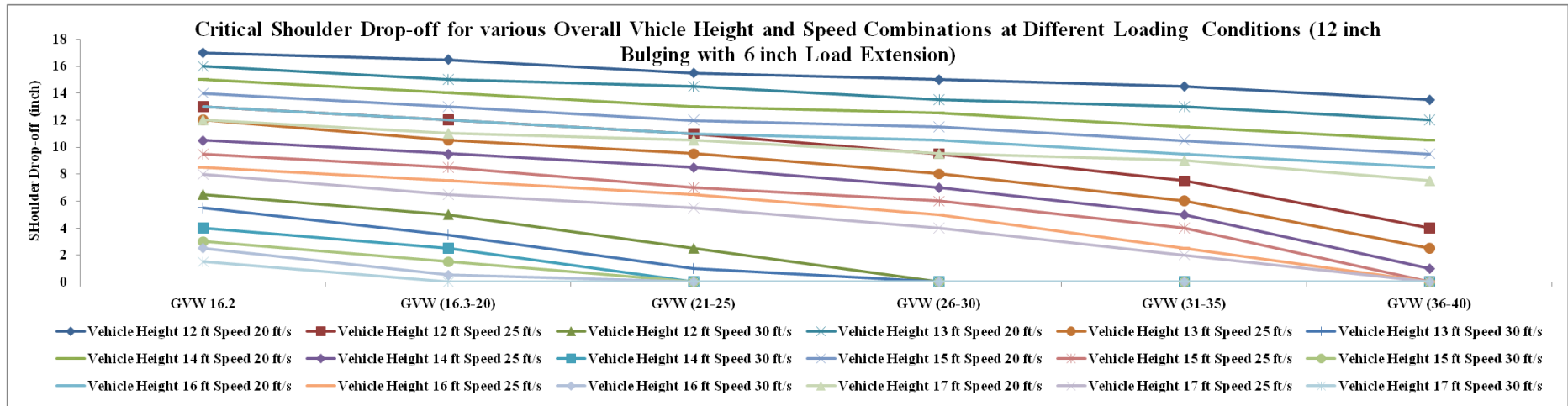
4.3.9.1 General Observations

For GVW greater than 30 ton, 30 ft/s speed produces large front slip angle than steering angle i.e. $(\delta - \alpha_f)$ is negative. Therefore, this speed is excluded in the analysis for GVW greater than 30 ton.

- **Effect of Overall Vehicle Height**

  o For every 1 ft increase in overall height, the shoulder drop-off for which rollover occurs decreases by about 1-1.5 inch. This decrease in critical shoulder drop-off remains the same while other parameters vary.

- **Effect of Speed**

  o For 5 ft/s increase in speed from 20 ft/s to 25 ft/s, the shoulder drop-off for which rollover occurs decreases by about 4 - 4.5 inch i.e. about 1 inch reduction of critical drop-off for every 1 ft/s increase in speed. That is Rollover may occur for lower values of drop-offs with increasing speed.

  o When speed is increased 5 ft/s from 25 to 30 ft/s, the reduction of critical drop-off enhances 1.5 times.

  o For certain weighing condition and overall height, at 30 ft/s speed the vehicle may overturn without any drop-off.

  o This reduction of drop-off varies with Gross Vehicle Weight. Table 4.4 illustrates the speed-drop-off relationship with weight.

Table 4.4: Reduction of Drop-off with Gross Vehicle Weight (GVW)

5 ft/s increase in speed	Decrease in Drop-off (inch)					
	GVW 16.2 Ton	GVW 16.3-20 Ton	GVW 21-25 Ton	GVW 26-30 Ton	GVW 31-35 Ton	GVW 36-40 Ton
20-25 ft/s	4 – 4.5	4 – 4.5	4.5 - 5	5 – 5.5	6.5 - 7	8.5 - 9
25-30 ft/s	6.5 - 7	7 – 7.5	8.5 - 9	10.5 - 11	---	---

- **Effect of Weight:**
    - Different weigh conditions affect the amount of reduction of critical shoulder drop-off with speed, overall height and loading extension. On average, the reduction of drop-off is about 0.5–1 inch up to GVW 25 ton, 1-1.5 inch up to GVW 35 ton and 3 inch up to GVW 40 ton.

- **Effect of Loading Extension**
    - For every 1 inch of extension of loading, the shoulder drop-off for which rollover occurs decreases 0.5 inch. That is Rollover may occur for lower values of drop-offs with the increase in loading extension. This decrease in critical shoulder drop-off remains the same while other parameters vary.

- **Effect of Pothole Depth**

It is seen from the analysis that existence of pothole on shoulder results the same effect as shoulder drop-off. Figure 4.14 clears the observation. The upper portion shows the results of 7.5 inch shoulder drop-off with pothole depth equal to zero and the lower portion gives the outcomes of 7.5 inch pothole depth without any shoulder drop-off. Both case yields rollover with equal rollover threshold.

w (ft)	H_c (ft)	b (ft)	T (ft)	a (inch)	d_2 (inch)	d_4 (inch)	x_1 (ft)	M_{tot} (kg)	V (ft/s)	R (ft)	M_{Empty} (kg)
8	4	6.5	6	2	7.5	0	4	30000	25	115.19	4595

Overturning Moment (in-lb)	M_O =	2.3E+06		Lateral Acceleration needed for Rollover			Lateral Acc. Of the Vehicle	
Stabilizing Moment (in-lb)	M_S =	2.2E+06		Rollover Threshold	a_y/g =	0.164	V^2/Rg	0.169
Difference between Moment	$M_O - M_S$ =	35567.281	Rollover Occur					

w (ft)	H_c (ft)	b (ft)	T (ft)	a (inch)	d_2 (inch)	d_4 (inch)	x_1 (ft)	M_{tot} (kg)	V (ft/s)	R (ft)	M_{Empty} (kg)
8	4	6.5	6	2	0	7.5	4	30000	25	115.19	4595

Overturning Moment (in-lb)	M_O =	2.3E+06		Lateral Acceleration needed for Rollover			Lateral Acc. Of the Vehicle	
Stabilizing Moment (in-lb)	M_S =	2.2E+06		Rollover Threshold	a_y/g =	0.164	V^2/Rg	0.169
Difference between Moment	$M_O - M_S$ =	35567.281	Rollover Occur					

Figure 4.15: Effect of Pothole Depth on Rollover

Hence, it can be said that, vehicle may overturn in cases where there is no drop-off but shoulder is ill-maintained. Therefore, shoulder should be maintained properly.

4.4 Overview

This chapter presents detailed systematic analysis of collected crash data. It also discusses about the process of model development and the analysis. For simplification of calculation, only rigid body model is analyzed. The next chapter provides simulation process.

CHAPTER 5

VALIDATION AND SIMULATION

5.1　Introduction

This chapter highlights general approaches and techniques of model validation found in different literatures. It also provides a direction for validating the developed model in this research work. A detailed description of simulation process is covered at the last of the chapter.

5.2　General Approaches and Techniques of Model Validation

Model validation is considered to be the process of determining to what extent the model's underlying fundamental rules and relationships are able to adequately capture the targeted emergent behavior, as specified within the relevant theory and as demonstrated by field data [44]. Toledo T. (2003) defines it as the purpose of determining the extent to which the model replicates the real system [45]. Therefore, validation is the process of determining the degree to which a model is an accurate representation of the real world.

A variety of validation techniques have been used by researchers in various scientific fields. Carley K.M. (1996) categorizes the techniques as grounding, calibrating, verifying, and harmonizing [46]. Grounding is generally used for establishing the face validity of a model. Calibrating is the process of tuning a model to fit detailed real data. If the parameters and the dependent variables match the real parameters and dependent variable, the model is considered to be calibrated. In verifying technique, the model's predictions are compared graphically or statistically with the real data. Harmonizing is to show that the theoretical assumptions embodied in the computational model are in harmony with the real world.

Hillston J. (2003) noted three approaches to model validation, which are expert intuition (expert's opinion about the model- sometimes it is called face validity), real system measurements (parameter calibration and depended variable verification) and theoretical results/analysis (outputs based on models underling theory coincides with the real world scenario) [47]. Another process of validation the author mentioned is to compare against the results or behavior of other models.

Sargent R.G. (2010) mentioned various validation techniques that include animation, comparison to other models, degenerate tests, event validity, extreme condition test, face validity, historical data validation, historical methods, internal validity, multi-stage validation, operational graphics, parameter variability/sensitivity analysis, predictive validation, traces etc. These techniques are used for verifying and validating the sub-models and the overall model [48].

Based on the above discussion, we can divide vehicle model validation in three categories, (i) Validation through controlled experiment, (ii) Validation by comparing the model with other models and (iii) Validation by simulation.

(i) Validation through Controlled Experiment

In controlled experiment, a test vehicle can be instrumented such that it can estimate and measure various parameters through different sensors. This method is often stated as full-scaled vehicle controlled experiment. Cameron J.T. (2005) mentioned such a test vehicle setup [49]. Steering sensor can measure steering angle, slip angle sensor can be used for measuring lateral slip angle of front and rear wheels. The accelerometer can help obtaining lateral acceleration. The accumulated data is then transferred to a PC through micro-controller.

As the full-scale method is costly, sometimes scaled-down vehicle is used for experiment. In this method, a small sized vehicle is constructed in such way that all the vehicle properties resemble the actual one and the parameters keep a certain ratio. This method requires full knowledge of assembly language programming and mechanical engineering.

(ii) Validation by Comparing the Model with Other Models

In this method, the model outputs are compared against the results of other validated model. But it should be used with care, as both may be invalid in the sense that they both may not represent the behavior of the real system accurately.

(iii) Validation by Simulation

Simulation software package makes the validation process much easier. Lots of simulation software are available such as PC-Crash, Truck-Sim, Car-Sim, crashViewer, Radioss (Altair ©), Crash CAE Automation, Matlab etc.

5.3   Simulation in Matlab Environment

Matlab has a wonderful simulation package called Simulink. The Simscape tool of SimuLink provides built-in vehicle dynamics (mechanical) functions. But it is only based on longitudinal dynamics. Lateral dynamics is not included. Therefore, user defined block library has to be created using Simscape language to include lateral dynamics. The block calculates front and rear slip angles, radius of turn, lateral acceleration, overturning moment and stabilizing moment.

Figure 5.1 demonstrates the simulink model. Three sub-models are used in the whole model, (i) Payload CG- to calculate the payload geometric CG, (ii) Whole Vehicle CG- to calculate the horizontal and vertical position of CG, and (iii) Inclination Angle (Theta)- to calculate the inclination angle of the vehicle. Figure 5.2 to 5.4 illustrates this sub-model. Steering angle, shoulder drop-off and velocity are controlled by a group of signal generator as shown in Figure 5.5. For the first two seconds the vehicle is running within normal condition with 35 ft/s speed. To avoid any surprise situation the driver applies brake at 2 sec to reduce speed to 25 ft/s. The total reduction time is 2 sec (2-4 sec). At 3 sec time steering wheel is rotated toward left for 1 sec to produce minus 5 degree steering angle (minus indicates turning to left and plus indicates turning to right) and then continued for another 1 sec. After that steering wheel is rotated toward right for 2 sec (5-7 sec) to maintain steering angle plus 5 deg. The drop-off input starts at 6 sec as during the time the vehicle encroaches to shoulder.

Figure 5.6 shows the lateral dynamics block. The block has some default parameters and requires some input to calculate lateral acceleration of the vehicle, overturning moment and stabilizing moment. The results of simulation can be viewed in scope block as shown in figure 5.7 to Figure 5.12. It is seen from the figures that at 7 sec, the vehicle will overturn.
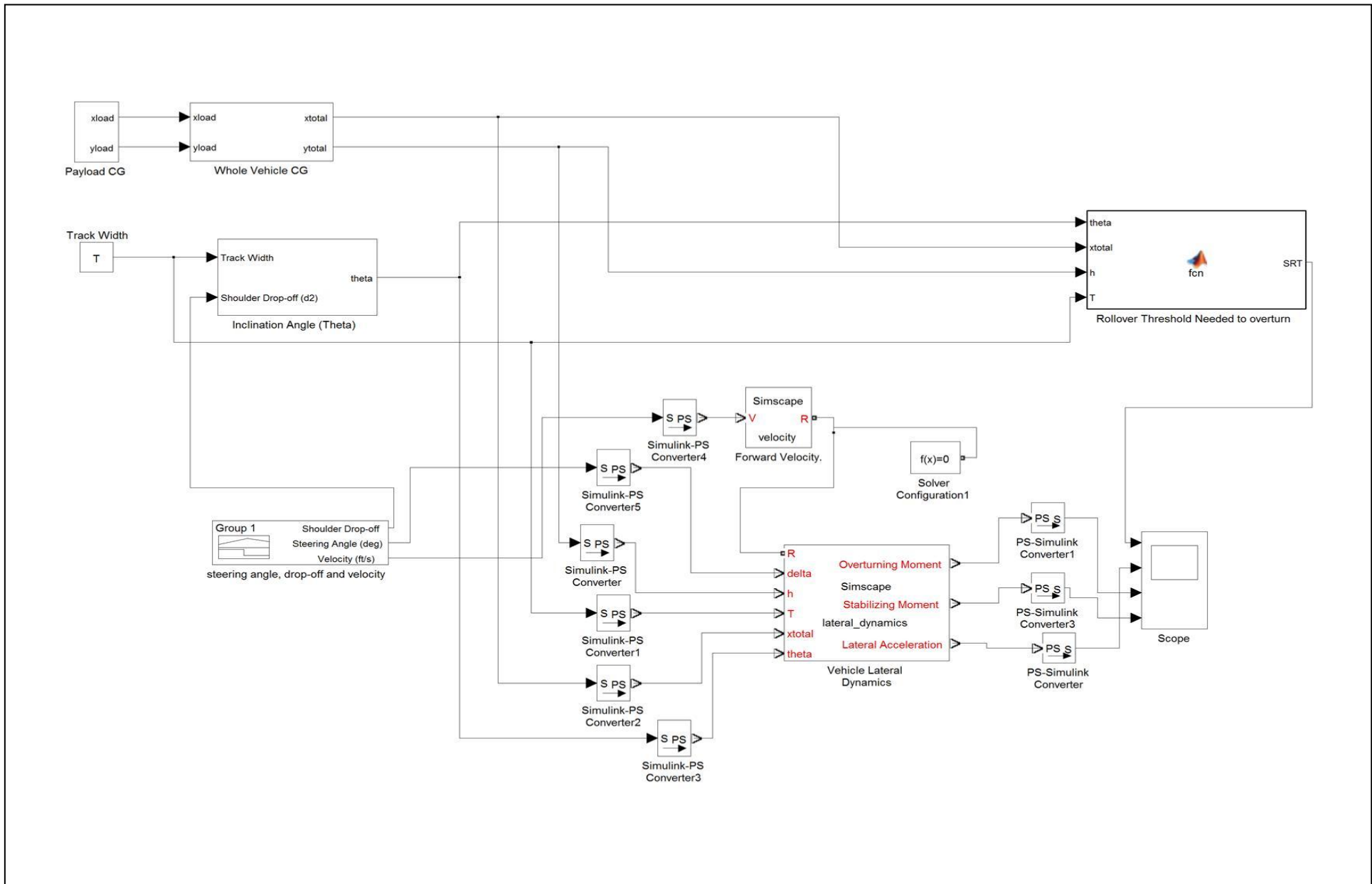
Figure 5.1: Matlab-Simulink Model

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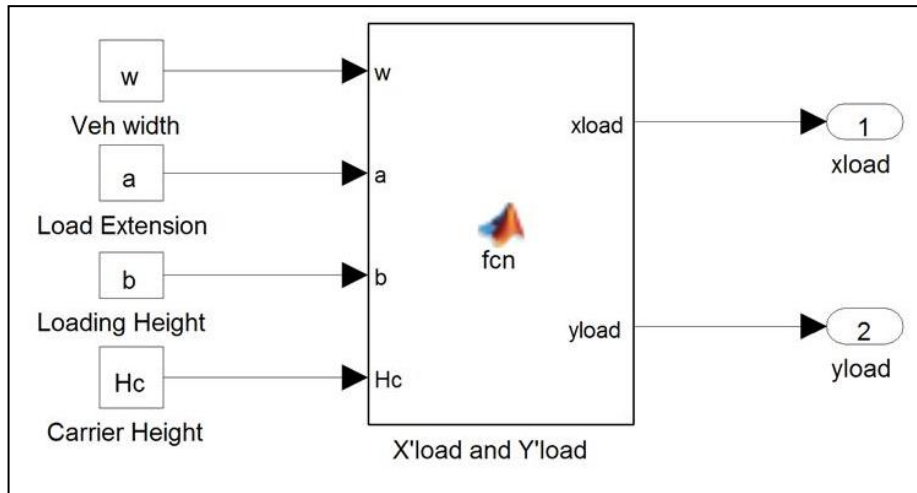
Figure 5.2: Payload CG Sub-model
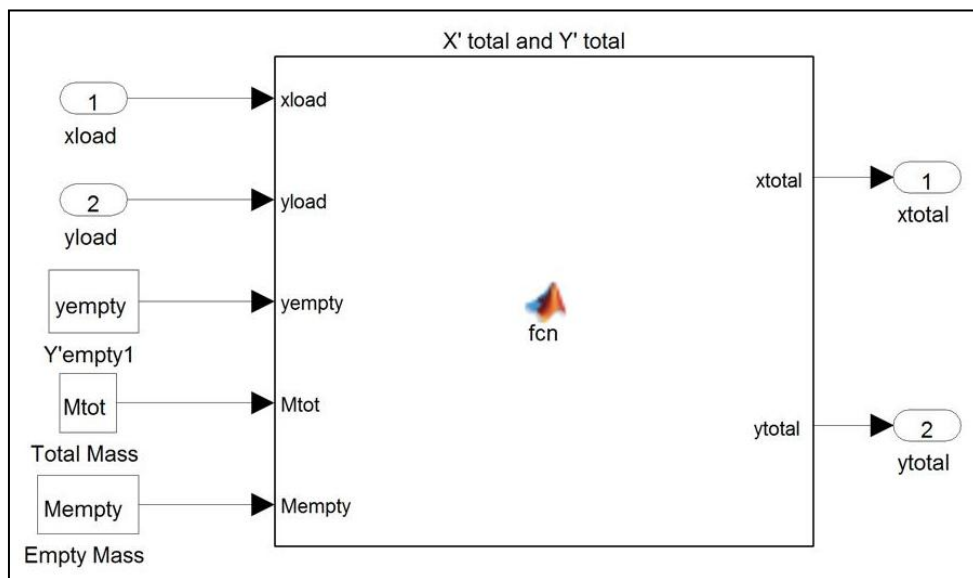
Figure 5.3: Whole Vehicle CG Sub-model
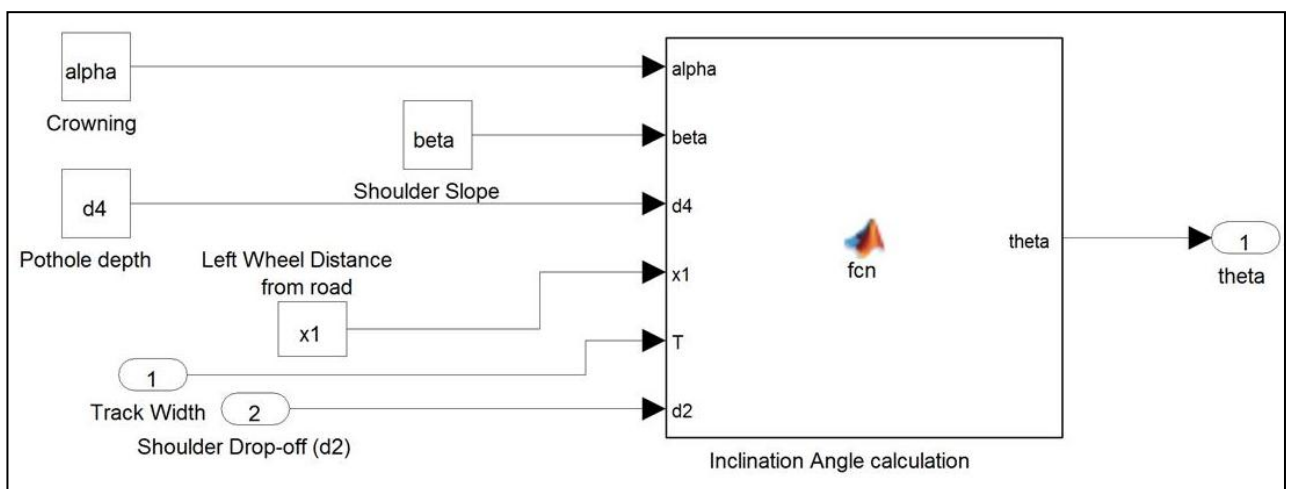
Figure 5.4: Inclination Angle Sub-model

75
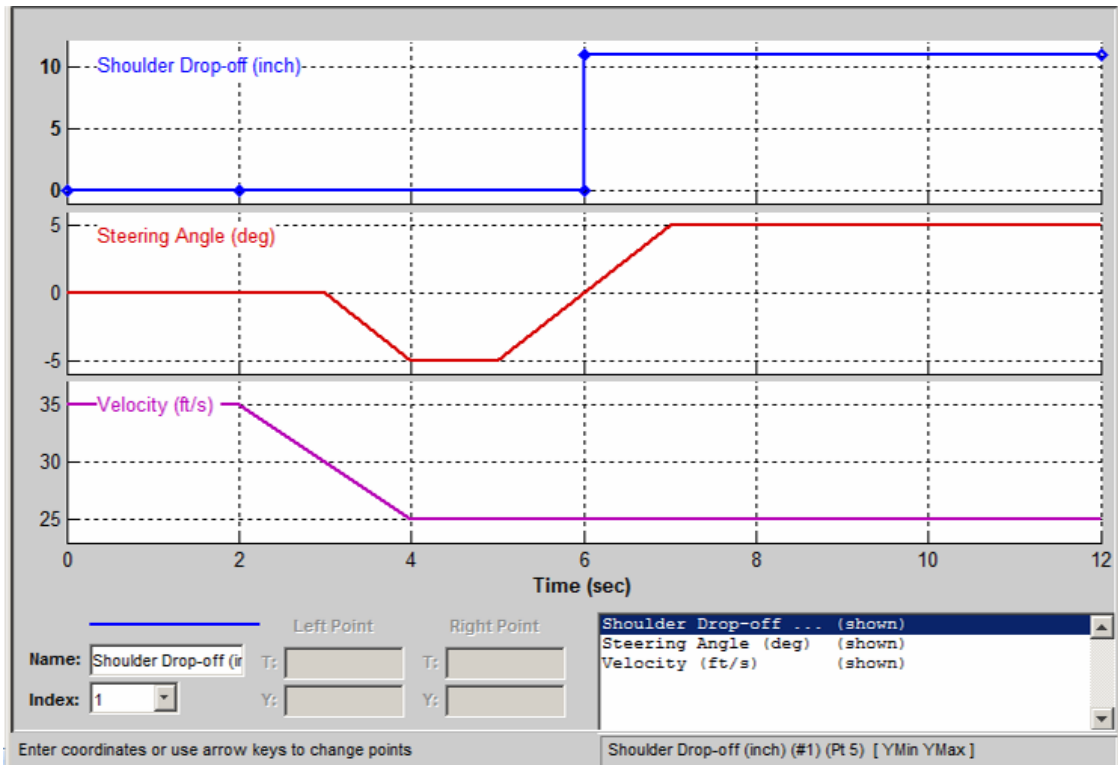
Figure 5.5: Input Signal Generator of Shoulder drop-off, Steering Angle and Velocity
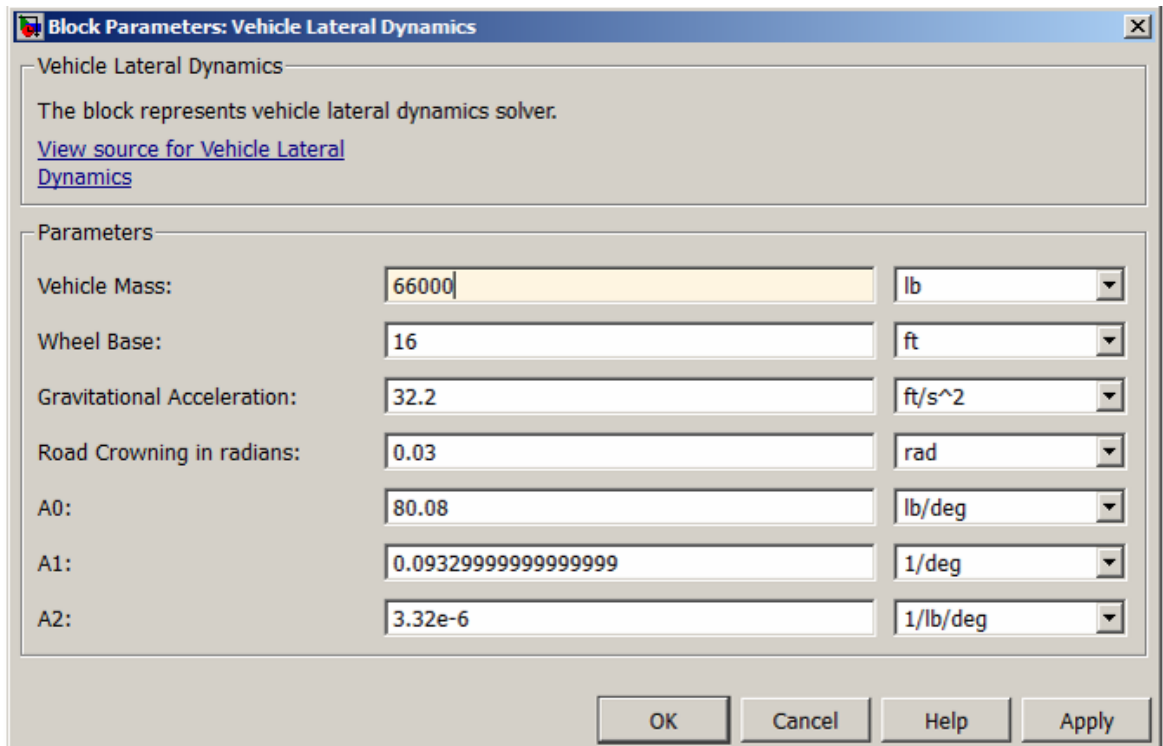
Figure 5.6: Vehicle Lateral Dynamics Block
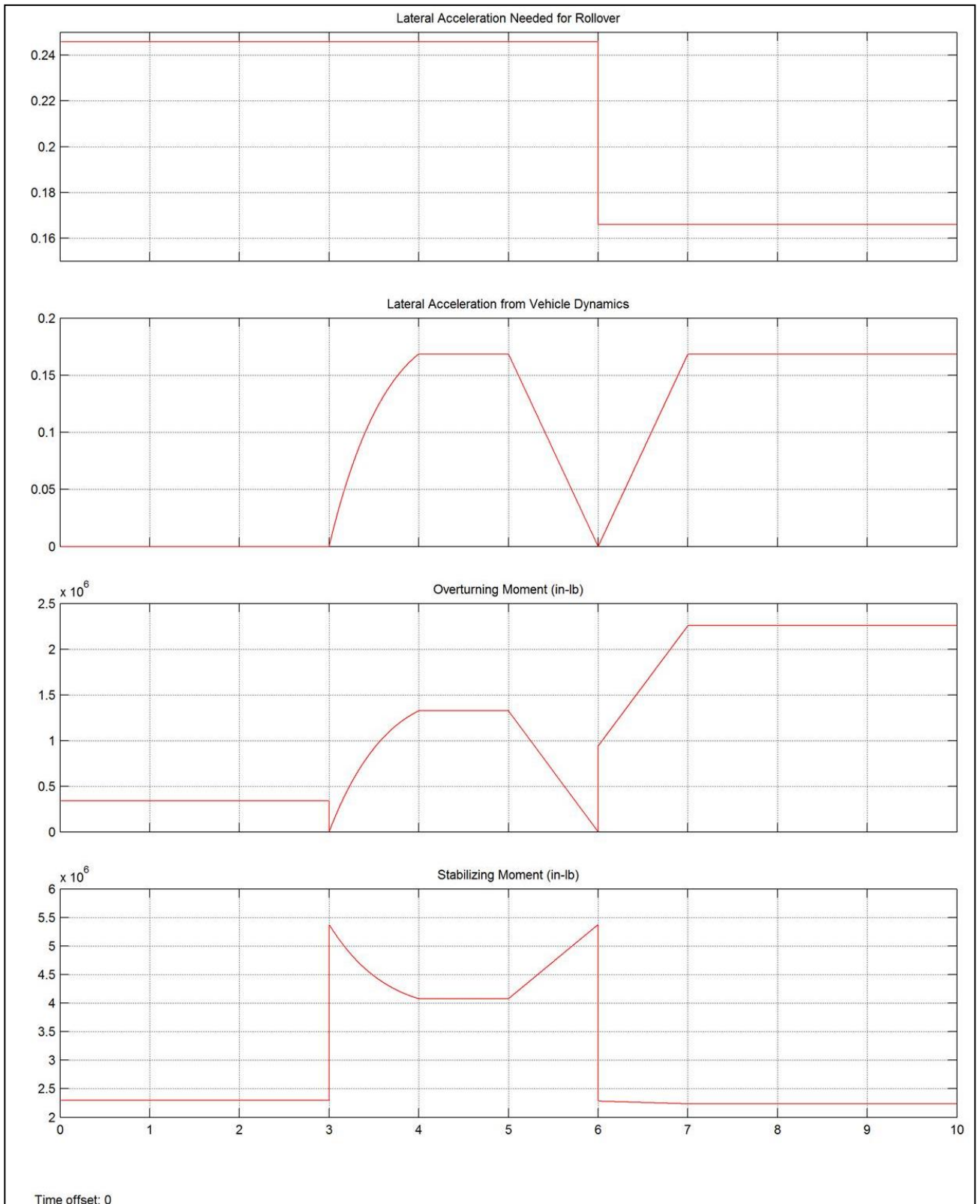
Figure 5.7: Results of the simulation (GVW 30 ton, overall vehicle height 17 ft, load extension 2 inch and shoulder drop-off 5.5 inch)
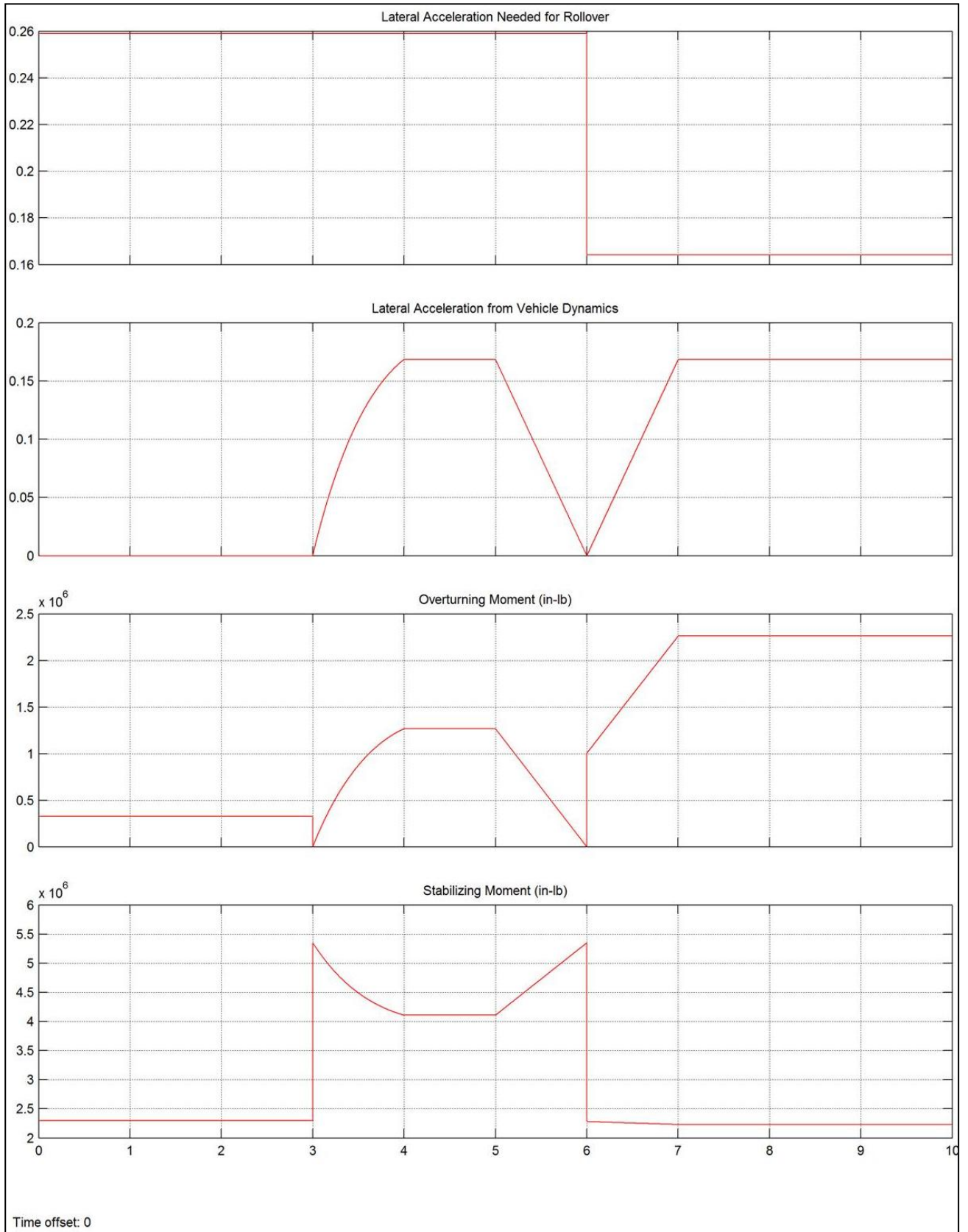
Figure 5.8: Results of the simulation (GVW 30 ton, overall vehicle height 16 ft, load extension 2 inch and shoulder drop-off 6.5 inch)
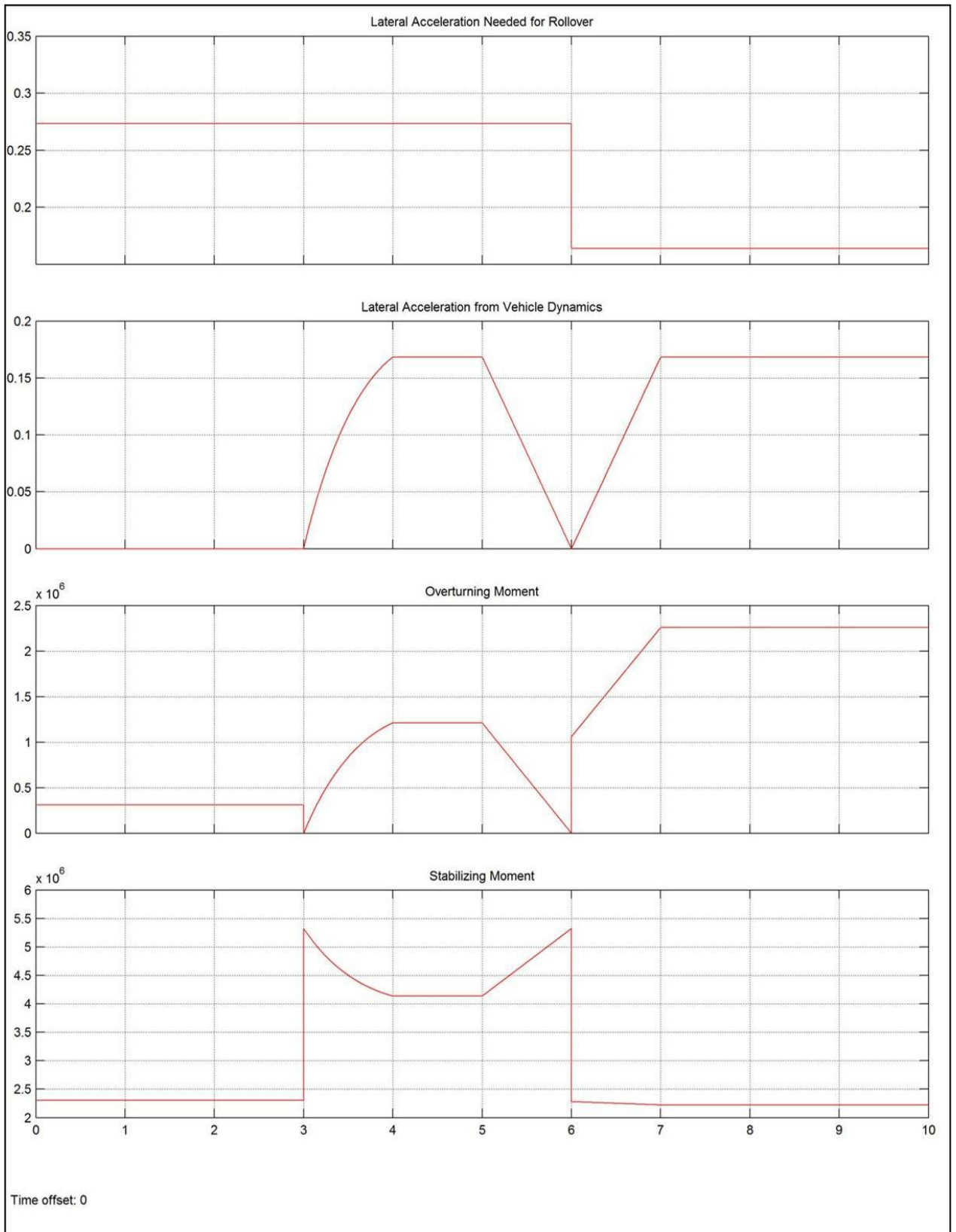
Figure 5.9: Results of the simulation (GVW 30 ton, overall vehicle height 15 ft, load extension 2 inch and shoulder drop-off 7.5 inch)
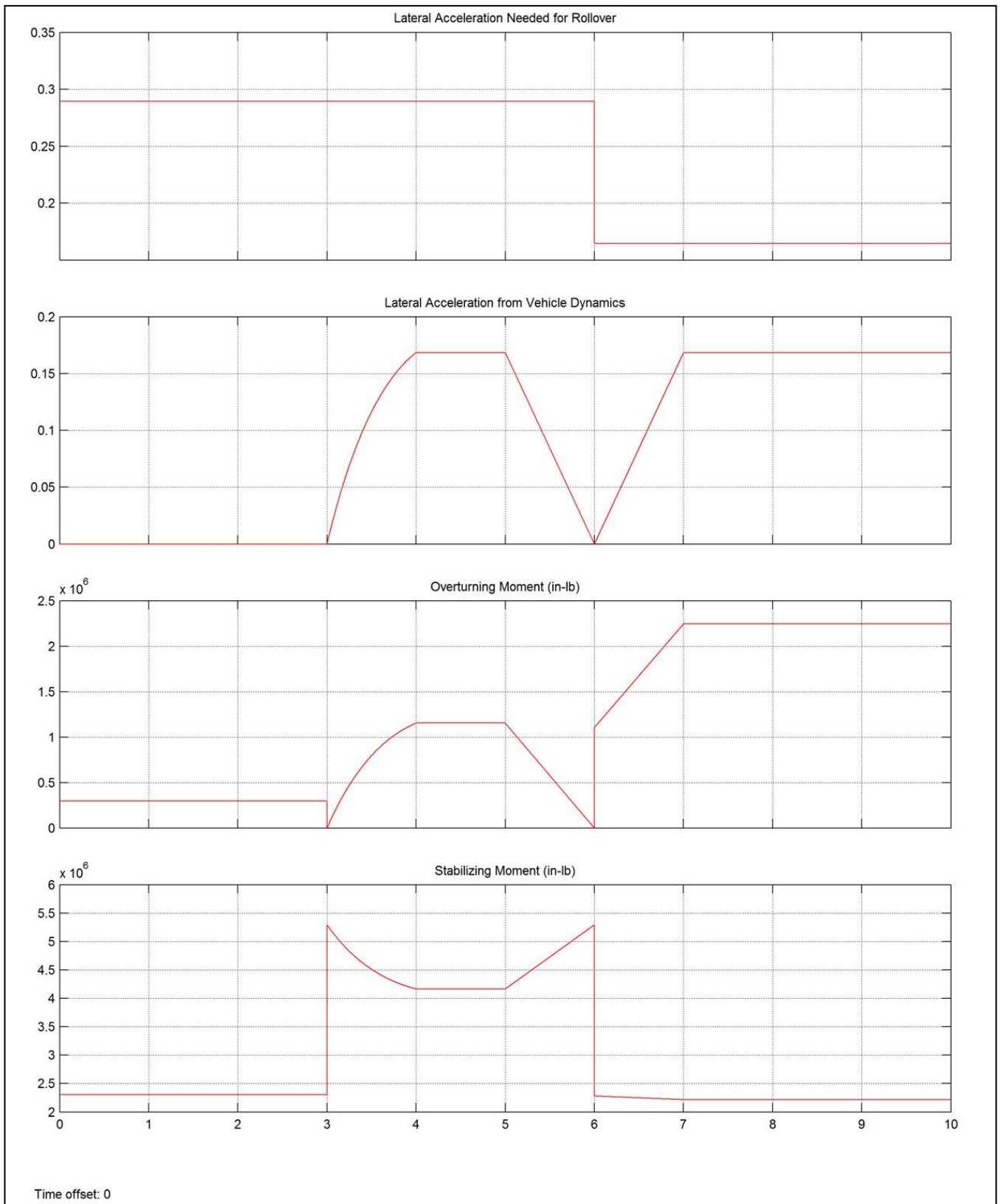
Figure 5.10: Results of the simulation (GVW 30 ton, overall vehicle height 14 ft, load extension 2 inch and shoulder drop-off 8.5 inch)
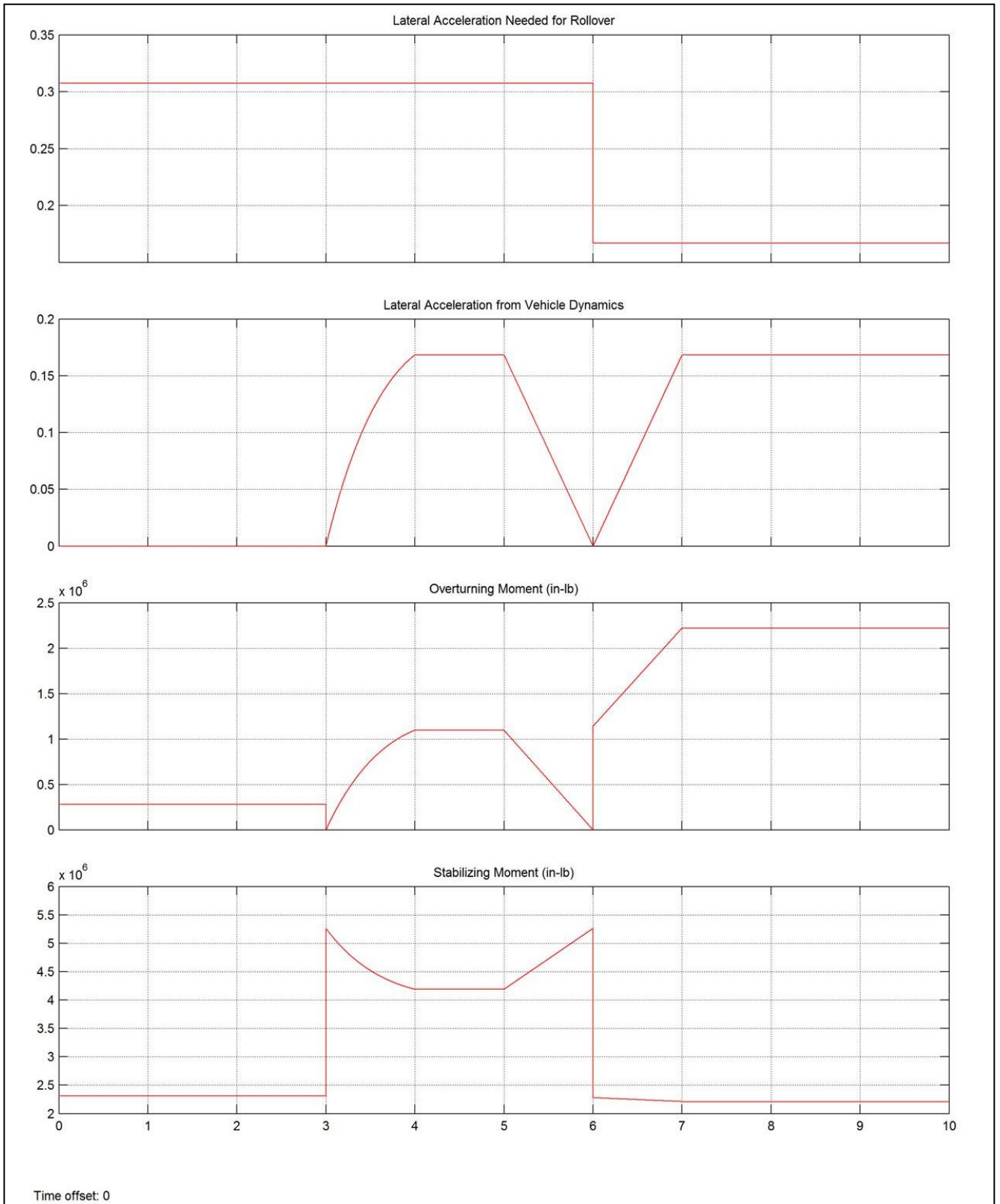
Figure 5.11: Results of the simulation (GVW 30 ton, overall vehicle height 13 ft, load extension 2 inch and shoulder drop-off 9.5 inch)

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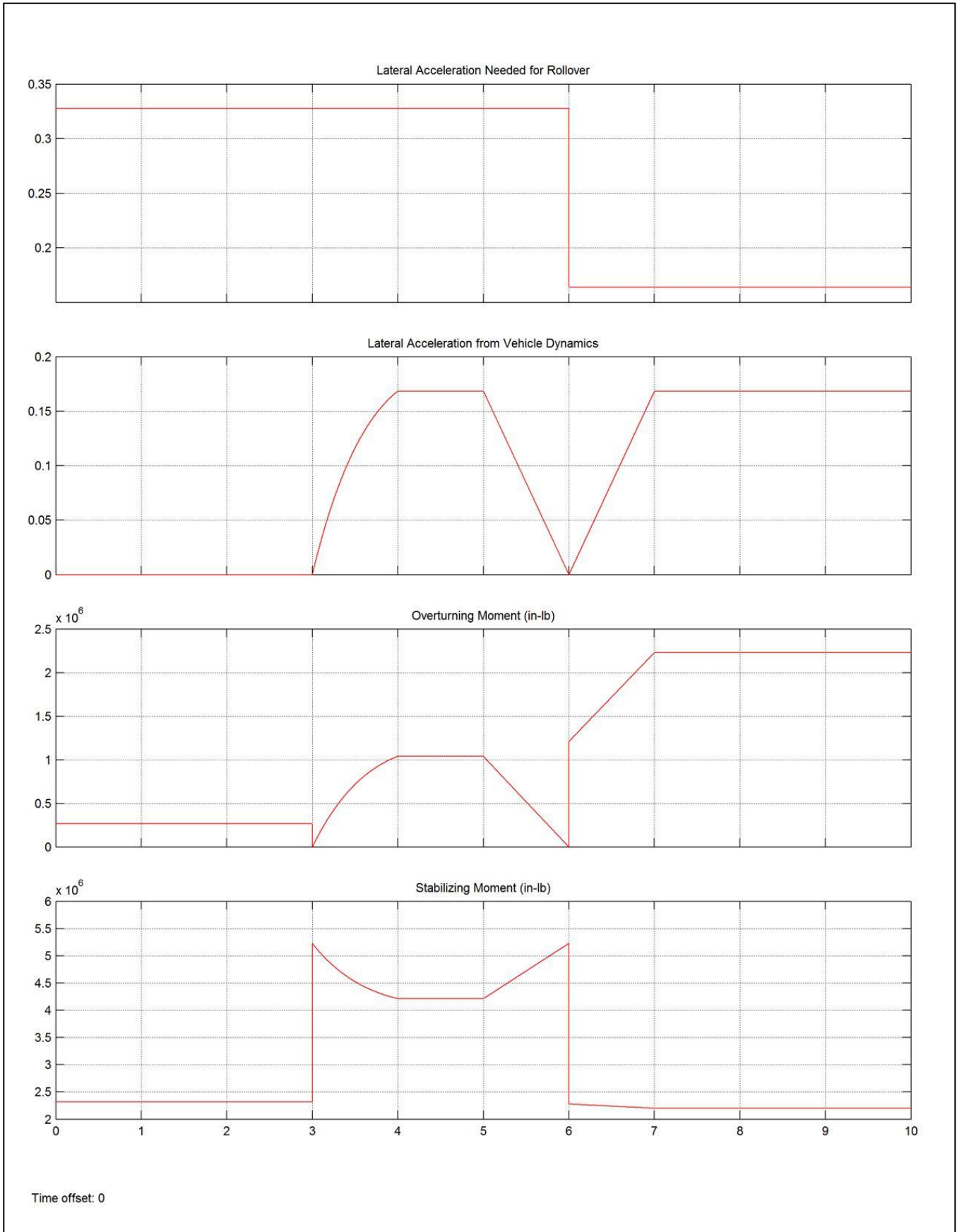
Figure 5.12: Results of the simulation (GVW 30 ton, overall vehicle height 12 ft, load extension 2 inch and shoulder drop-off 11 inch)

5.4 Overview

The simulation has been done for the vehicle with GVW 66000lb (30 ton) and load extension 2 inch, for overall vehicle height 12 ft to 17 ft. The result of the model analysis using MS Excel 2007 coincides with the simulation results. Hence, it can be said that the results of the simulation is quite satisfactory.

CHAPTER 6

CONCLUSIONS AND
RECOMMENDATIONS

6.1 Introduction

The study has been intended to identify critical overturning criteria for single vehicle Run-off-Road crashes in Bangladesh. This type of accident may occur for special road geometric characteristics, driver behavior or vehicular characteristics. The rollover model and the analysis deals with shoulder drop-off as special geometric characteristics, vehicle speed as driver behavior, gross weight, overall height and load bulging as vehicular characteristics. From the model analysis and observations of results, some recommendations and guideline are provided in the following sections.

6.2 Specific Findings based on Model Analysis

6.2.1 Standard Vehicles with GVW 16.2 Ton

When trying to re-enter to roadway from shoulder,

- o Vehicles with standard overall height 14 ft may overturn at 4-6 inch drop-offs at 30 ft/s speed in any loading extension. With 17 ft height, the same vehicle may overturn at 1.5-3 inch drop-offs at 30 ft/s speed in any loading extension.

- o Vehicles with standard overall height 14 ft may overturn at 10.5-12.5 inch drop-offs at 25 ft/s speed in any loading extension. With 17 ft height, the same vehicle may overturn at 8-10 inch drop-offs at 25 ft/s speed in any loading extension.

- o Vehicles with standard overall height 14 ft may overturn at 15-17 inch drop-offs at 20 ft/s speed in any loading extension. With 17 ft height, the same vehicle may overturn at 12-14 inch drop-offs at 20 ft/s speed in any loading extension.

6.2.2 Vehicles with GVW 16.3-20 Ton

When trying to re-enter to roadway from shoulder,

- Vehicles with standard overall height 14 ft may overturn at 2.5-4 inch drop-offs at 30 ft/s speed in any loading extension. With 17 ft height, the same vehicle may overturn at 0-1.5 inch drop-offs at 30 ft/s speed in any loading extension.

- Vehicles with standard overall height 14 ft may overturn at 9.5-11.5 inch drop-offs at 25 ft/s speed in any loading extension. With 17 ft height, the same vehicle may overturn at 6.5-9 inch drop-offs at 25 ft/s speed in any loading extension.

- Vehicles with standard overall height 14 ft may overturn at 14-16 inch drop-offs at 20 ft/s speed in any loading extension. With 17 ft height, the same vehicle may overturn at 11-13.5 inch drop-offs at 20 ft/s speed in any loading extension.

6.2.3 Vehicles with GVW 21-25 Ton

When trying to re-enter to roadway from shoulder,

- Vehicles with standard overall height 14 ft may overturn at 0-2 inch drop-offs at 30 ft/s speed in any loading extension. With 17 ft height, the same vehicle may overturn without any drop-offs at 30 ft/s speed in any loading extension.

- Vehicles with standard overall height 14 ft may overturn at 8.5-10.5inch drop-offs at 25 ft/s speed in any loading extension. With 17 ft height, the same vehicle may overturn at 5.5-7.5 inch drop-offs at 25 ft/s speed in any loading extension.

- Vehicles with standard overall height 14 ft may overturn at 13-16.5 inch drop-offs at 20 ft/s speed in any loading extension. With 17 ft height, the same vehicle may overturn at 10.5-12.5 inch drop-offs at 20 ft/s speed in any loading extension.

6.2.4   Vehicles with GVW 26-30 Ton

When trying to re-enter to roadway from shoulder,

- o Vehicles with standard overall height 14 ft may overturn without any drop-offs at 30 ft/s speed in any loading extension.

- o Vehicles with standard overall height 14 ft may overturn at 7-9 inch drop-offs at 25 ft/s speed in any loading extension. With 17 ft height, the same vehicle may overturn at 4-6 inch drop-offs at 25 ft/s speed in any loading extension.

- o Vehicles with standard overall height 14 ft may overturn at 12.5-14.5 inch drop-offs at 20 ft/s speed in any loading extension. With 17 ft height, the same vehicle may overturn at 9.5-12 inch drop-offs at 20 ft/s speed in any loading extension.

6.2.5   Vehicles with GVW 31-35 Ton

When trying to re-enter to roadway from shoulder,

- o Vehicles with standard overall height 14 ft may overturn at 5-7.5 inch drop-offs at 25 ft/s speed in any loading extension. With 17 ft height, the same vehicle may overturn at 2-4.5 inch drop-offs at 25 ft/s speed in any loading extension.

- o Vehicles with standard overall height 14 ft may overturn at 11.5-14 inch drop-offs at 20 ft/s speed in any loading extension. With 17 ft height, the same vehicle may overturn at 9-11 inch drop-offs at 20 ft/s speed in any loading extension.

6.2.6   Vehicles with GVW 36-40 Ton

When trying to re-enter to roadway from shoulder,

- o Vehicles with standard overall height 14 ft may overturn at 1-4.5 inch drop-offs at 25 ft/s speed in any loading extension. With 17 ft height,

the same vehicle may overturn without drop-off with loading extension beyond 1 inch.

- o Vehicles with standard overall height 14 ft may overturn at 10.5-13.5 inch drop-offs at 20 ft/s speed in any loading extension. With 17 ft height, the same vehicle may overturn at 7.5-10.5 inch drop-offs at 20 ft/s speed in any loading extension.

6.3 Recommendations based on Model Analysis

6.3.1 Recommendations for Standard Vehicles with GVW 16.2 Ton

- Considering road geometric condition and local trend of overall vehicle height in Bangladesh, vehicles with any overall height must maintain a speed less than 25 ft/s while they re-enter to roadway from shoulder.
- Considering road geometric condition in Bangladesh, overall vehicle height should be restricted to 14 ft.
- Considering road geometric condition and local trend of overall vehicle height in Bangladesh, the loading must not be extended beyond 3 inch on both sides.
- Considering driver behavior, local trend of overall height and bulging, with strict restriction to less than 25 ft/s speed, the shoulder drop-off must not exceed 7.5 inch with no existence of pothole on shoulder.

6.3.2 Recommendations for Vehicles with GVW 16.3-20 Ton

- Considering road geometric condition and local trend of overall vehicle height in Bangladesh, vehicles with any overall height must maintain a speed of 20 ft/s while they re-enter to roadway from shoulder.
- Considering road geometric condition in Bangladesh, overall vehicle height should be restricted to 14 ft.
- Considering road geometric condition and local trend of overall vehicle height in Bangladesh, there must not be any bulging.
- Considering driver behavior, local trend of overall height and bulging, there must not be any shoulder drop-off. But it is not feasible. Hence, with strict

restriction to less than 25 ft/s speed, the drop-off must not exceed 6 inch with no existence of pothole on shoulder.

6.3.3 Recommendations for Vehicles with GVW 21-25 Ton

- Considering road geometric condition and local trend of overall vehicle height in Bangladesh, vehicles with any overall height must maintain a speed of 20 ft/s while they re-enter to roadway from shoulder.
- Considering road geometric condition in Bangladesh, overall vehicle height should be restricted to 13 ft.
- Considering road geometric condition and local trend of overall vehicle height in Bangladesh, there must not be any bulging.
- Considering driver behavior, local trend of overall height and bulging, there must not be any shoulder drop-off. But it is not feasible. Hence, with strict restriction to less than 25 ft/s speed, the drop-off must not exceed 5 inch with no existence of pothole on shoulder.

6.3.4 Recommendations for Vehicles with GVW 26-30 Ton

- Considering road geometric condition and local trend of overall vehicle height in Bangladesh, vehicles with any overall height must maintain a speed of 20 ft/s while they re-enter to roadway from shoulder.
- Considering road geometric condition in Bangladesh, overall vehicle height should be restricted to 12 ft.
- Considering road geometric condition and local trend of overall vehicle height in Bangladesh, there must not be any bulging.
- Considering driver behavior, local trend of overall height and bulging, there must not be any shoulder drop-off. But it is not feasible. Hence, with strict restriction to less than 25 ft/s speed, the drop-off must not exceed 3.5 inch with no existence of pothole on shoulder.

6.3.5   Recommendations for Vehicles with GVW 31-35 Ton

- Considering road geometric condition and local trend of overall vehicle height in Bangladesh, vehicles with any overall height must maintain a speed of less than 20 ft/s while they re-enter to roadway from shoulder.
- Considering road geometric condition in Bangladesh, overall vehicle height should be restricted to less than 12 ft.
- Considering road geometric condition and local trend of overall vehicle height in Bangladesh, there must not be any bulging.
- Considering driver behavior and local trend of overall height and bulging, there must not be any shoulder drop-off. But it is not feasible. Hence, with strict restriction to 25 ft/s speed, the drop-off must not exceed 2 inch with no existence of pothole on shoulder.

6.3.6   Recommendations for Vehicles with GVW 36-40 Ton

- Considering road geometric condition and local trend of overall vehicle height in Bangladesh, vehicles with any overall height must maintain a speed below 20 ft/s while they re-enter to roadway from shoulder.
- Considering road geometric condition in Bangladesh, overall vehicle height should be restricted to less than 12 ft.
- Considering road geometric condition and local trend of overall vehicle height in Bangladesh, there must not be any bulging.
- Considering driver behavior and local trend of overall height and bulging, there must not be any shoulder drop-off. But it is not feasible. Hence, with strict restriction of speed below 23 ft/s, the drop-off must not exceed 2 inch with no existence of pothole on shoulder.

6.3.7   Final Recommendations

From the above discussion, it can be concluded that,

- Considering road geometric condition and local trend of overall vehicle height in Bangladesh, vehicles with gross weight up to 30 ton must maintain a safe speed below 25 ft/s (27.5 kmph) and vehicles with gross weight between 30

and 40 ton must maintain a safe speed below 20 ft/s while they re-enter to roadway from shoulder.

- Considering road geometric condition in Bangladesh, vehicles with gross vehicle weight up to 20 ton, overall vehicle height should be restricted to 14 ft; with gross weight between 20 and 25 ton, overall vehicle height should be restricted to 13 ft; with gross weight between 25 and 30 ton, overall vehicle height should be restricted to 12 ft; with gross weight between 30 and 40 ton, overall vehicle height should be restricted to less than 12 ft.
- Considering road geometric condition and local trend of overall vehicle height in Bangladesh, there must not be any bulging.
- Considering driver behavior and local trend of overall height and bulging, shoulder drop-off must not exceed 2 inch with strict speed restriction to less than 23 ft/s (25.2 kmph) and with no existence of pothole on shoulder.

6.3.8 Special Guidelines for Roads and Highways Authority in Bangladesh

- Existence of pothole on shoulder may lead to rollover without any shoulder drop-off. Therefore, the authority should maintain the shoulder properly.
- It is often found that the authority carry out the re-surfacing of pavement only without proper maintenance of shoulder. It yields a vertical difference between pavement and the adjacent shoulder. Sometimes shoulder is found to be discontinuous that could affect the stability of vehicle and lead the vehicle to lose control and rollover. Therefore, under the road maintenance program both the pavement and the shoulder should be re-surfaced and maintained properly.
- According to Axle Load Control Authority, the average overloading ranges between 20 and 30 ton (44000-66000 lbs). Pavement should be designed considering this axle loading.

6.3.9 Special Guidelines for Bangladesh Road Transport Authority

More often the tires of truck in Bangladesh are overinflated for operating in high speed. The size of the footprint in contact with the road is lesser for an overinflated tire than normal. Therefore, it could be damaged more easily when running over potholes or debris in the road. Besides, when a overloaded truck runs for a longer

period, tire air pressure increases with time for increase in air temperature. The increase in tire pressure along with large load could result in tire burst without any geometric fault and could lead the vehicle to running out of road. Hoque M.S. and Hasan M.R. (2006) conducted a research to identify vehicular involvement in road accident [50]. The authors showed that trucks account for about 61% of the tire burst related accidents on highway N-9 (Jamuna Approach Road). The authors also identified that the most burst prone tire is the rear-left combination comprising 50% of the incidences. They pointed out that the left wheels are forced to carry more weight than right ones for the camber provided in carriageway. This extra loading along with the general overloading of trucks increase tire pressure and temperature and hence result in tire bursting and overturn. Hence, BRTA should maintain random field inspection to check the truck tire pressure along with overloading.

6.4 Future Research

The research work reported in this thesis focused on the analysis based on rigid vehicle model of vehicle rollover. As stated early in this chapter, it only deals with shoulder drop-off on straight road segment as geometric feature, vehicle speed as driver behavior, gross weight, overall height and load bulging as vehicular features. It is evident that road accident is a complex interaction of road user, vehicle, and infrastructures with a number of variables and parameters. Considering the limitation of this research work, the following aspects are recommended for further studies:

i. The model analysis and simulation would be based on vehicle model with suspension compliance. To come closer to reality the model should consider transient roll effect of vehicle body as well as roll and yaw moment of inertia.

ii. The study would be expanded to develop model on curved road considering super elevation.

iii. The effect of weather i.e. effect of road friction in wet condition and hydroplaning would also be included.

iv. Controlled experiment should be done to validate the model analysis result with test result.

v. A warning device/system might be developed to warn the driver.

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