Journal of Civil Engineering (IEB), 42 (2) (2014) 161-169

Journal of Civil Engineering IEB

An analytical model for single unit heavy truck rollover accidents in Bangladesh

Shahnewaz Hasanat-E-Rabbi[1] and Md. Shamsul Hoque[2]

[1]Accident Research Institute
Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh
[2]Department of Civil Engineering
Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh

Received 19 September 2013

Abstract

Run-Off-Road (ROR) 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. Running off road may occur as an aftermath of single vehicle accident or any other accidents. Single vehicle ROR accident results in either overturning on the shoulder or hitting off road objects. Accident data analysis shows that in Bangladesh, more than 21% overturning accident involves heavy trucks. Drivers are often blamed for these accidents due to reckless driving. But it is not as simple. Overturning of vehicles is due to the result of complex interaction among vehicle loading pattern, speed, road geometric features etc. Considering these facts, a rollover model is developed which correlates special vehicle loading features such as loading width, height and load shifting with overturning accident in terms of rollover threshold. This paper highlights the model development process and model analysis.

Keywords: Heavy Truck, Rollover model, Loading height, Load shifting

1. Introduction

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. 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. Accident and casualty statistics of 13 years (1998-2010) shows that among various types of accidents overturning accident is about 9% of total accidents and is responsible for 15% of total fatalities (Table 1). Heavy vehicles usually buses and heavy trucks are mostly involved in this type of accident. Figure 1 clearly demonstrates that more than 21% overturning accident involves heavy truck.

Table 1
Accident and Casualty Statistics from 1998-2010

Accident Type	Number of Accident	% of Total Accident	Number of Casualty	% of Total Casualty
Head-On	6720	14.66	17316	23.22
Rear-End	6927	15.11	10634	14.26
Right-angle	507	1.11	757	1.02
Side-swipe	2715	5.92	4581	6.14
Overturn	3887	8.48	11227	15.06
Hit Object on road	417	0.91	673	0.90
Hit Object off road	1122	2.45	2427	3.25
Hit Parked Vehicle	1048	2.29	1859	2.49
Hit Pedestrian	20788	45.36	22813	30.59
Hit Animal	27	0.06	43	0.06
Other	1673	3.65	2238	3.00
Total	45831	100	74568	100

**Source: Micro-computer Accident Analysis Package (MAAP5) Analysis*

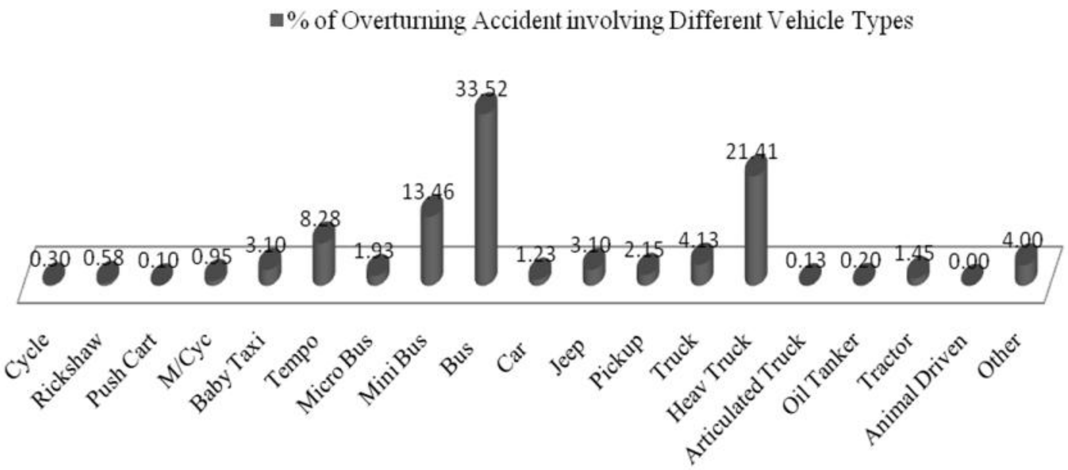

Fig. 1. Percentage of Overturning Accident involving Different Vehicle Types

Singh (2005) stated in his thesis that 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.

According to road accident classification system in Bangladesh, overturning off road and hit object off road fall in the category of ROR crashes as stated. Analysis in Microcomputer Accident Analysis Package (MAAP5) demonstrates that overturning of vehicles to the left of carriageway on straight road comprises of about more than half of the single vehicle ROR crashes in Bangladesh (Table 2). In this writing only overturning to the left on straight road is termed as rollover and considered for modelling.

Table 2
Distribution of Single Vehicle Run-off-road Accident

Types of Accident	Number of Accident	% of Total
Overturning to the left of carriageway (Straight road)	549	52.74
Overturning to the right of carriageway (Straight road)	159	15.27
Hit Objet off road to the left (Straight road)	254	24.40
Hit Objet off road to the right (Straight road)	55	5.28
Overturning to the left of carriageway (Curved road)	14	1.34
Overturning to the right of carriageway (Curved road)	6	0.58
Hit Objet off road to the left (Curved road)	3	0.29
Hit Objet off road to the right (Curved road)	1	0.10
Total	1041	100

**Source: Micro-computer Accident Analysis Package (MAAP5) Analysis*

2. Motivation behind Model Development

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. Actually, 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 geometrical data like height of shoulder drop-off, pothole depth etc. and vehicle related data like loading height, width etc., it necessitates rollover accidents to be analyzed analytically.

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 height and weight. Heavily loaded vehicles with high height usually have higher CG. 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.

Shoulder drop off is another factor to rollover. It can reduce vehicle stability and impede a driver's ability to handle a vehicle. 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. Consequently a rollover moment develops.

Considering these facts, an analytical model is developed which relates these factors with rollover of heavy truck and presented in this paper.

3. Derivation of the Model

For the model development purpose, following assumptions are made:

- The roadway is assumed straight road segment with a dry surface that 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 straight.

- The vehicle is assumed 2 axle 6 wheeler truck without any defect.
- Bulging/shifting of load 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.

The model is based on the ‘Quasi-Static Rollover Model’; a fundamental model in vehicle dynamics. The quasi-static model deals with rollover threshold while the vehicle is in a steady state turn. Gillespie (1992) explains the pros and cons about the model. 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’. It is expressed as ‘Static Stability Factor (SSF)’.

$$\text{Rollover Threshold or SSF} = a_y / g = T/ 2h \quad (1)$$

where is a_y the lateral acceleration, g is gravitational acceleration, T is track width of vehicle and h is the centre of gravity height of the vehicle.

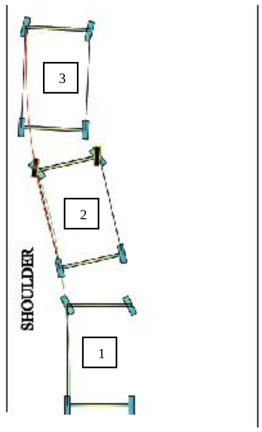

Fig. 2. Schematic Diagram of Vehicle Leaving off and Returning to Roadway

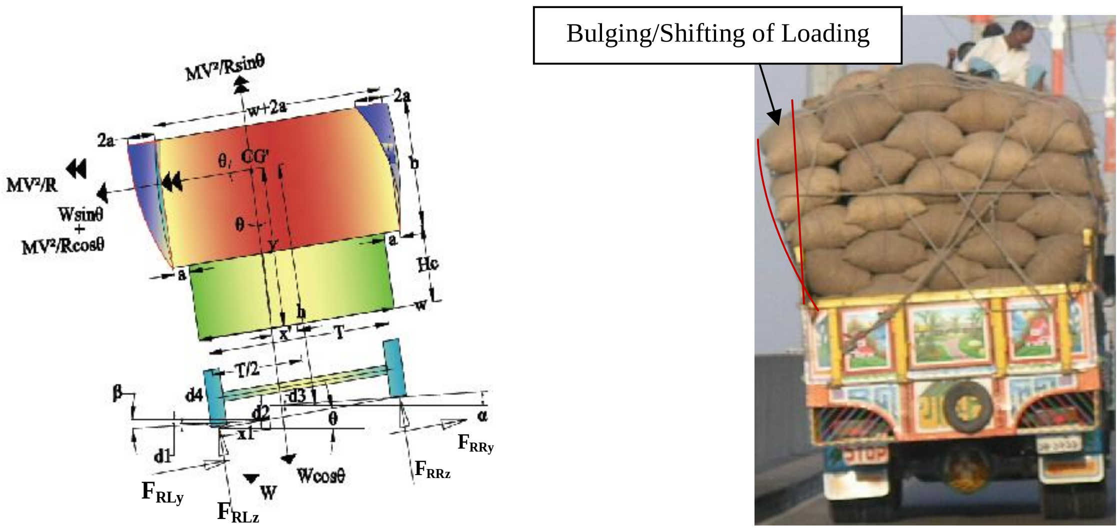

Fig. 3. Forces and reactions of a heavy truck in rigid vehicle model (left) and bulging/shifting of load on a truck (right)

To determine and quantify the effect of ‘Shoulder Drop-off’ with/without pothole on it and the effect of ‘Bulging/shifting of Loading’ on rollover threshold, some extra parameters are included in the 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 2 as position (1). For the steering to the left, 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 3 illustrates the forces and reactions acting on a heavy truck while the vehicle is in position (3).

According to the Figure 3, the cross slope angle with horizontal is α and the shoulder slope angle with horizontal is β. The height of loading above the carrier is ‘b’. The loading expands in both side of carrier with distance ‘a’ and hence the total freight top width is w+2a. Let us assume that for bulging, the left portion of loading is shifted ‘2a’ distance towards left from previous position. The right side of the loading is also moved ‘2a’ towards left. For simplification of calculation, the side of the actual loading is assumed straight and after bulging, the shape is assumed semi parabolic. 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. The new position of CG is calculated with the help of center of gravity theorem of composite body.

The weight (W =mg) of the truck acts vertically downward through the CG. The weight and the lateral force (MV^2/R, where R is the radius of turning) 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,

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

where, h = y' + height of truck bed form level ground
Inclination angle (θ) is calculated using Figure 4,

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

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

At the instant when overturning is about to occur, $F_{RRz} = 0$, equation (2) can be written as,

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

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

or, $g. \cos \theta. (T/2 - x') - g. \sin \theta. h = ay. \sin \theta. (T/2 - x') + ay. \cos \theta. h$

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

Dividing both side by cos θ yields

$$a_y /g = [T/2 - x' - h. \tan \theta] / [h + (T/2 - x'). \tan \theta] \quad (3)$$

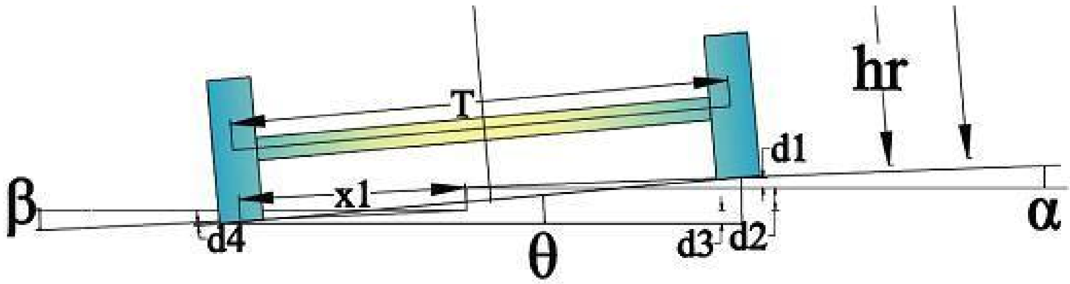

Fig. 4. Calculation of inclination angle

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 (equation 1), the numerator of equation (3) 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. Overturning moment and stabilizing moment are calculated using the following equations according to Figure 3.

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

Where, R is the radius of turning and is calculated using 'Cornering Equation' of vehicle dynamics for a given values of gross weight and speed as described by Gillespie (1992).

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

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)

4. Model Analysis and Results

To determine the effect of loading height and overloading condition based on whether the vehicle overturns or not and to get the value of rollover threshold, calculations are performed in MS Excel 2007. For the calculation purpose, initial values are so chosen for some model parameters that those would fall in the range of current practice and trend in Bangladesh.

Table 3
Summary of the Model Analysis

	Gross Vehicle Weight 16.2 Ton					Gross Vehicle Weight 25 Ton				
	Overall Height (ft)	Rollover Threshold a_y/g	Overturning Moment (in-lb)	Stabilizing Moment (in-lb)	Rollover Occurs (Y/N)	Overall Height (ft)	Rollover Threshold a_y/g	Overturning Moment (in-lb)	Stabilizing Moment (in-lb)	Rollover Occurs (Y/N)
Load Extension a = 0 inch	12	0.298	927169	1576145	N	12	0.282	1594863	2260436	N
	13	0.280	972085	1531260	N	13	0.263	1679340	2176000	N
	14	0.264	1016967	1486409	N	14	0.246	1763772	2091610	N
	15	0.249	1061816	1441590	N	15	0.231	1848158	2007265	N
	16	0.235	1106632	1396804	N	16	0.217	1932501	1927731	Y
Load Extension a = 1 inch	12	0.293	928467	1551342	N	12	0.277	1597777	2216245	N
	13	0.275	973510	1503215	N	13	0.258	1682591	2126000	N
	14	0.259	1018475	1455828	N	14	0.241	1767270	2037054	N
	15	0.244	1063375	1408978	N	15	0.225	1851842	1949042	N
	16	0.230	1108220	1362530	N	16	0.211	1936327	1899027	Y
Load Extension a = 2 inch	12	0.289	929699	1525942	N	12	0.272	1600612	2170965	N
	13	0.270	974858	1474585	N	13	0.253	1685754	2074922	N
	14	0.254	1019896	1424688	N	14	0.235	1770676	1981451	N
	15	0.239	1064841	1375833	N	15	0.220	1855433	1889813	N
	16	0.225	1109710	1327752	N	16	0.206	1940061	1869794	Y
Load Extension a = 3 inch	12	0.284	930869	1499965	N	12	0.267	1603378	2124629	N
	13	0.265	976134	1445392	N	13	0.247	1688843	2022801	N
	14	0.249	1021239	1393009	N	14	0.230	1774006	1924839	N
	15	0.233	1066224	1342179	N	15	0.214	1858948	1844281	Y
	16	0.220	1111112	1292494	N	16	0.200	1943721	1840060	Y

	Gross Vehicle Weight 30 Ton					Gross Vehicle Weight 35 Ton				
	Overall Height (ft)	Rollover Threshold a_y/g	Overturning Moment (in-lb)	Stabilizing Moment (in-lb)	Rollover Occurs (Y/N)	Overall Height (ft)	Rollover Threshold a_y/g	Overturning Moment (in-lb)	Stabilizing Moment (in-lb)	Rollover Occurs (Y/N)
Load Extension a = 0 inch	12	0.277	2048787	2569111	N	12	0.274	2617946	2753930	N
	13	0.258	2160513	2457398	N	13	0.255	2764907	2685880	Y
	14	0.241	2272244	2345679	N	14	0.238	2912102	2685820	Y
	15	0.226	2383984	2308966	Y	15	0.222	3059540	2685757	Y
	16	0.212	2495735	2308970	Y	16	0.208	3207232	2685692	Y
Load Extension a = 1 inch	12	0.272	2054113	2512382	N	12	0.269	2629621	2680559	N
	13	0.253	2166599	2393092	N	13	0.249	2778621	2650938	Y
	14	0.236	2278956	2277167	Y	14	0.232	2927635	2647652	Y
	15	0.220	2391229	2275004	Y	15	0.216	3076748	2644983	Y
	16	0.206	2503451	2273219	Y	16	0.202	3226019	2642768	Y
Load Extension a = 2 inch	12	0.267	2059440	2454195	N	12	0.263	2641685	2623363	Y
	13	0.247	2172701	2327314	N	13	0.244	2792850	2615116	Y
	14	0.230	2285703	2244662	Y	14	0.226	2943812	2608625	Y
	15	0.214	2398533	2240355	Y	15	0.211	3094732	2603377	Y
	16	0.200	2511249	2236808	Y	16	0.197	3245718	2599041	Y
Load Extension a = 3 inch	12	0.262	2064786	2394583	N	12	0.258	2654192	2590789	Y
	13	0.242	2178844	2260102	N	13	0.238	2807665	2578452	Y
	14	0.224	2292515	2211480	Y	14	0.221	2960724	2568775	Y
	15	0.209	2405927	2205052	Y	15	0.205	3113601	2560976	Y
	16	0.195	2519165	2199771	Y	16	0.191	3266455	2554550	Y

- 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
- Shoulder drop-off is assumed 4 inch
- 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 5°.
- Four types of loading condition are chosen for the model; one for standard vehicle with GVW 35640 lb (16.2 ton) and three others are overloaded vehicle with GVW 55000, 66000 and 77000 lb (25, 30 and 35 ton respectively).
- Speed is chosen as 25 ft/s (27.5 km/h).

At first, using ‘cornering equation’ radius of turn (R) is calculated for the given speed. 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 3 inch. At this stage, rollover threshold is obtained for overall height of 12 - 16 ft. The summary of the analysis is given in the following Table 3.

Figure 5 illustrates the effect of different loading conditions on rollover threshold for various load extensions with variable height. Rollover threshold decreases with increase in vehicle weight (i.e. load weight), vehicle height (i.e. load height) and load extension. The larger the weight, height and load extension the lesser is the value of roll threshold and at certain point critical condition occurs.

It is clearly seen from Figure 5 that there will occur no rollover for standard load condition (GVW 16.2 ton) even with high height and large load extension. For GVW 25 ton, 16 ft height yields critical condition for any load extension. For GVW 30 ton, height of 15 ft or more yields critical condition for any load extension. Load extension of 2 inch or more is critical for 14 ft height. For GVW 35 ton, rollover occurs for 14 ft height with any load extension. However, 12 ft height and 1 inch load extension is very critical in this case.

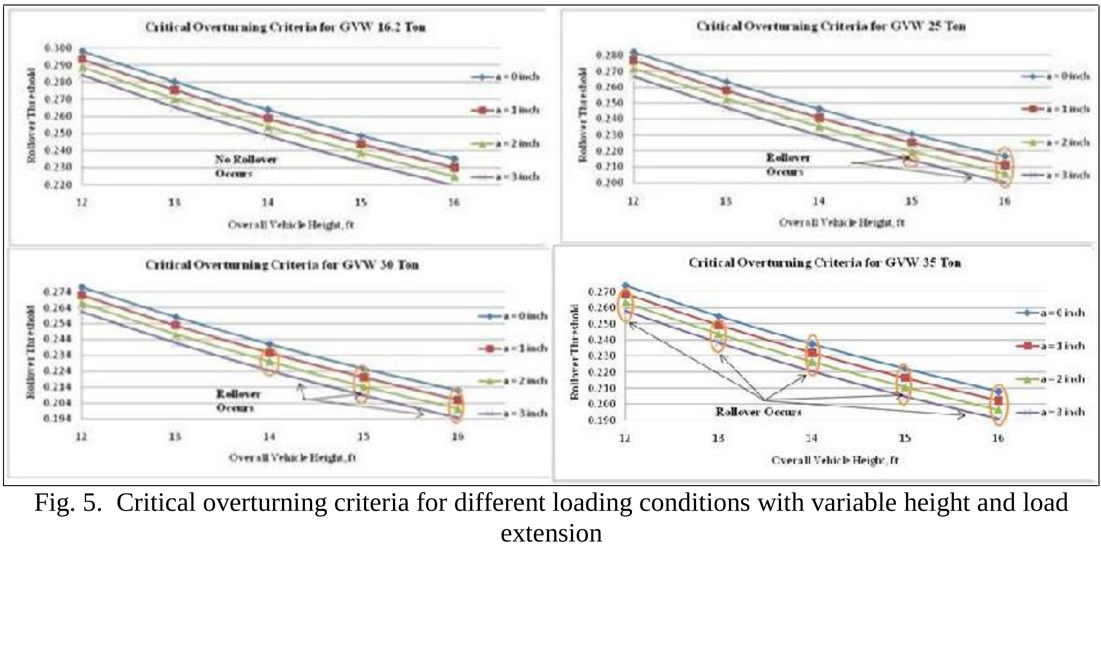

Fig. 5. Critical overturning criteria for different loading conditions with variable height and load extension

5. Conclusions

In terms of the transportation system, socio-economic condition, driver behavior, road geometric condition, vehicle loading condition etc. Bangladesh is a country with some special peculiarities that differs a lot from the others. Hence, in providing suggestions according to the results of the rollover model, some Bangladeshi practices are considered. The specific recommendations are:

- Vehicle must not be overloaded in such a way that the gross vehicle weight exceeds 30 ton.
- Overall vehicle height must be restricted to 14 ft or less.
- Load extension of more than 1 inch must be prohibited.

The research is based on rigid vehicle model, no suspension effect or inertial effect is considered and it is not validated through field experiment. To come closer to reality, in future the model should be modified and transient roll effect of vehicle body as well as roll and yaw moment of inertia would be considered.

References

Gillespie, T.D. (1992) *Fundamentals of Vehicle Dynamics*. Society of Automotive Engineers, Warrendale, PA,

Singh, P. (2005) *A study of fatal run off road crashes in the state of Florida*. M.Sc. thesis, Department of Civil Engineering, Florida State University, U.S.A.