Heavy Truck Rollover Model for Single Vehicle Run–off–Road Crashes in Bangladesh

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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 the road may occur as an aftermath of single vehicle accident or any other incidents. 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. What may be the factors behind these accidents? Is it due to the driver performance only or is due to other factors? To find out the answer of the question analytically, a rollover model has been 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 results.

Keywords: ROR crashes; heavy truck crashes; Rollover model; loading height; load shifting

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1.0 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 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 [1]. 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 [2].

Table 1 Accident and casualty statistics 1998-2010

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

Source: Microcomputer Accident Analysis Package (MAAP5) Analysis
Singh, P. 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 [3]. 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 modeling.

Table 2 Distribution of single vehicle run-off-road accident

<table>
<thead>
<tr>
<th>Types of Accident</th>
<th>Number of Accident</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overturning to the left of carriageway (Straight road)</td>
<td>549</td>
<td>52.74</td>
</tr>
<tr>
<td>Overturning to the right of carriageway (Straight road)</td>
<td>159</td>
<td>15.27</td>
</tr>
<tr>
<td>Hit Object off road to the left (Straight road)</td>
<td>254</td>
<td>24.40</td>
</tr>
<tr>
<td>Hit Object off road to the right (Straight road)</td>
<td>55</td>
<td>5.28</td>
</tr>
<tr>
<td>Overturning to the left of carriageway (Curved road)</td>
<td>14</td>
<td>1.34</td>
</tr>
<tr>
<td>Overturning to the right of carriageway (Curved road)</td>
<td>6</td>
<td>0.58</td>
</tr>
<tr>
<td>Hit Object off road to the left (Curved road)</td>
<td>3</td>
<td>0.29</td>
</tr>
<tr>
<td>Hit Object off road to the right (Curved road)</td>
<td>1</td>
<td>0.10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1041</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Source: Microcomputer Accident Analysis Package (MAAP5) Analysis

2.0 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 [2]. Actually, these are the general causal factors behind many road accidents. 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 and vehicle related data like loading height, width, it necessitates rollover accidents to be analyzed analytically.

Hasanat-E-Rabbi, S. [3] stated in his thesis that 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. Vehicles with high center 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 [4].

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.

3.0 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, T. [5] 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)’ [5].

\[
\text{Rollover Threshold or SSF} = \frac{a_y}{g} = \frac{T}{2h} \tag{1}
\]

Where;

- \(a_y\) = lateral acceleration,
- \(g\) = gravitational acceleration,
- \(T\) = track width of vehicle and
- \(h\) = centre of gravity height of the vehicle.

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)].

![Figure 2](image2.png)

Figure 2 Schematic diagram of vehicle leaving off and returning to roadway

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 ‘\(\alpha\)’ and the shoulder slope angle with horizontal is \(\beta\). 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.

![Figure 3](image3.png)

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

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,

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

Where,

- \(h = y' + \text{height of truck bed from level ground}\)
Inclination angle ($\theta$) is calculated using Figure 4, 
\[
\sin \theta = \frac{(d_1 + d_2 + d_3 + d_4)}{T} \\
\Rightarrow \theta = \sin^{-1} \left( \frac{(T - x_1) \sin \alpha + x_1 \sin \beta + d_2 + d_4}{T} \right)
\]

At the instant when overturning is about to occur, \(F_{RRz} = 0\), Equation (2) can be written as,
\[
[W. \cos \theta - (MV^2/R). \sin \theta]. (T/2 - x') - [W. \sin \theta + (MV^2/R). \cos \theta]. h = 0
\]
\[
\Rightarrow [Mg. \cos \theta - (May). \sin \theta]. (T/2 - x') - [Mg. \sin \theta + (May). \cos \theta]. h = 0
\]
\[As \ V^2/R \ is \ the \ lateral \ acceleration\]
\[
\Rightarrow ay/g = \frac{\cos \theta \cdot (T/2 - x') - h \cdot \tan \theta}{h + \sin \theta \cdot (T/2 - x') + \tan \theta}
\]

The term \(ay/g\) 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, \(MO > Stabilizing \: Moment, \: MS\). 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.

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

\[\delta = \frac{57.3 \cdot (L/R)}{R^2} \cdot \frac{(Wf/Ca - Wr/Ca)}{g} \cdot \frac{V^2}{R^g}
\]

\[where, \ \delta = \text{Steering angle at the front wheels (deg)} \]
\[Wf = \text{Load on front axle (lb)} \]
\[Wr = \text{Load on rear axle (lb)} \]
\[Ca = \text{Cornering stiffness of the front tires (lb/deg)} \]
\[Cr = \text{Cornering stiffness of the rear tires (lb/deg)} \]
\[L = \text{Wheel base (ft)} \]
\[R = \text{Radius of turn (ft)} \]
\[V = \text{Vehicle speed (fps)} \]
\[g = \text{Gravitational acceleration (32.2 f/s^2)} \]

\[\delta = 57.3 \cdot (L/R) \cdot \frac{(Wf/Ca - Wr/Cr)}{g} \cdot \frac{V^2}{R^g}
\]

**4.0 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.

- 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 Table 3.
<table>
<thead>
<tr>
<th>Load Extension</th>
<th>Gross Vehicle Weight 16.2 Ton</th>
<th>Gross Vehicle Weight 25 Ton</th>
<th>Gross Vehicle Weight 30 Ton</th>
<th>Gross Vehicle Weight 35 Ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>a = 0 inch</td>
<td>Overall Height (ft)</td>
<td>Rollover Threshold a/g</td>
<td>Overturning Moment (in-lb)</td>
<td>Stabilizing Moment (in-lb)</td>
</tr>
<tr>
<td>----------------</td>
<td>-------------------------------</td>
<td>-----------------------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>12</td>
<td>0.298</td>
<td>927169</td>
<td>1576145</td>
<td>N</td>
</tr>
<tr>
<td>13</td>
<td>0.280</td>
<td>972085</td>
<td>1531260</td>
<td>N</td>
</tr>
<tr>
<td>14</td>
<td>0.264</td>
<td>1016967</td>
<td>1486409</td>
<td>N</td>
</tr>
<tr>
<td>15</td>
<td>0.249</td>
<td>1061816</td>
<td>1441590</td>
<td>N</td>
</tr>
<tr>
<td>16</td>
<td>0.235</td>
<td>1106632</td>
<td>1396804</td>
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<td>a = 1 inch</td>
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<td>973510</td>
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<td>15</td>
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<td>0.225</td>
<td>1109710</td>
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<td>a = 3 inch</td>
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<td>N</td>
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<tr>
<td>16</td>
<td>0.220</td>
<td>1111112</td>
<td>1292494</td>
<td>N</td>
</tr>
</tbody>
</table>

Table 3 Summary of the model analysis
Figure 5 Critical overturning criteria for different loading conditions with variable height and load extension

It is clearly seen from Figure 5 that no rollover will occur 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.

5.0 CONCLUSIONS

In terms of the transportation system, socio-economic condition, driver behavior, road geometric condition, vehicle loading condition, the local condition of Bangladesh has some special peculiarities that differ 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