The Rollover Prediction and Prevention of Bullet Proof Vehicles for Improved Stability

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Abstract: Bullet proof vehicles (BPVs) are special purpose vehicles manufactured by carrying out modification of existing vehicle mostly inside compartment which contains basically hidden box of steel built inside the vehicle. Most critical areas of a bullet proof vehicle are protection of persons and maneuverability of the vehicle. Difficulties being faced in producing BPVs includes identification of suitable vehicle roll over models from the literature, parameters selection, comparison of these models and formulation of model new one exclusive to bullet proof vehicles produced in developing countries. This work presents an initial investigation to narrow down parameters selection to analyze roll over tendency in Bullet proof vehicles and offer a suitable methodology to avoid expected Bullet Proof Vehicle rollover due to dangerous driving maneuvers. Different scenarios are to be considered while roll model formulation of these special purpose bullet proof vehicles. Not only the add on armored protection drastically increase the weight of the vehicle which is the most critical area but also some special cases which are specific to BPV maneuverability also arises. The effect of such instable tendency on rollover require investigation not captured by existing normal vehicle models and further supports the idea for its investigation of roll over tendency. It has been learnt that uneven distribution of weight develops certain moments in a BPV which can create hidden instability tendency in a BPV.

Keywords: Bullet Proof Vehicle, Rollover Thresh hold, LTR, Roll moment of inertia

Introduction
1. Increase in terrorist activities in the world specially after 9/11 has lead to requirement of protection equipment. Auto industry of developing countries is directly affected due to this changing environment[1]. Bullet proof vehicles are very effective protection equipment for the persons detailed on security duties. In developing countries security organizations are handicapped due to non availability of sophisticated security equipment like jammers and cameras security infrastructure, as compare to developed countries where a proper set up for security exits and governments are spending huge amount of budget for developing and purchasing of electronic gadgetry for security purpose[2]. The importance of BPV after realizing these problems could not be denied. BPV are special purpose vehicles mostly developed after modification of the same vehicles that are available commercially. This is done to hide the protection level of the vehicle[3]. The armoring kits available to provide protection are made up of many different materials. Different materials are used to develop armoring kits in commercial vehicles. Some time steel, aluminum and sometimes composite materials are used for this purpose. After going through series of ballistic and penetration tests materials are selected. In material selection for a BPV different important fields considered are protection level, engine horse power available space and clearance available in the inner side of the trims of the vehicle, type of suspension used, brake system and types of tire. After analyzing all these factors an armoring kit is selected. The weight of the armoring kit is very critical as it can directly affect the performance of a BPV . This extra weight of the armoring kit is to be carried by the vehicle all the time and it may affect the suspension, acceleration performance and brakes of the vehicle. After the installation of armoring kit ,different tests are performed to check suspension, brakes and acceleration performance of the vehicle. Among other important areas, stability of a BPV also require special attention for its desired maneuverability during emergency situations. In developing countries which are exposed to terrorist activities and day by day fear of insecurity is increasing ,security organizations are adopting the idea of using BPVs not only for VIP protection but also during operations against terrorists. Although all relevant data of these BPVs performance during these operations is not publically available but some reports regarding the cause of some operations failure has been discussed[4]. In many cases the success was never achieved against these terrorists due to poor maneuverability of the BPV .This maneuverability problem occurred due to hidden instability tendency present in the vehicle which was exposed during that operation. Soon after that it was felt that protection
understanding. But there is still a possibility that some
presented in a graphical form for better
calculated. The results obtained after iterations are
these parameters are varied and their affect is
calculated. Now the results obtained are again produced in graphical form and compared to the results obtained. If the results show similarity in trend and values then own model
considered valid. The other procedure for model validation is to compare it with some test data calculated experimentally by some valid transport
research organization. In most of the cases the test data calculated by National Highway Traffic Safety
administration of USA has been used as own model validation where as NHTSA has very accurate and
sophisticated experimental set up of where different fleet of vehicles are selected for this purpose [8]. This
fleet of vehicles may consist of more than 20 vehicles. Selection of these vehicles has been done on the basis of accident data which has been collected by NHTSA to analyze the causes of these accident and ultimately to reduce its happening [9]. Those vehicles which have more number of accidents are selected for analysis purpose. After evaluation of accident results it was felt that rollover of vehicle is also a major contributor in these accidents [10]. Further roll over was divided into sub classes for better understanding. These two classes are tripped and untripped vehicles roll over. In tripped vehicle roll over the vehicle rolls due to some external obstruction or cause. Where as in untripped roll over mainly single vehicle is considered which rolls over due to instability present in the system of the vehicle and roll over has occurred without any external obstruction [5]. As in this paper we will also focus only on untripped roll over, so only this class of roll over will be discussed. For untripped rollover of vehicles the vehicles having maximum number of accidents in accidents history are considered for roll over analysis in NHTSA. Different kinds of tests are performed and values of effected parameters which are calculated experimentally through electronic sensors. These results are not meant to comment for comparison among different car manufactures. This data is only collected for reference of automobile researchers in order to enable them for better vehicle system dynamics, analysis. This collected data is not
only available in values and numbers but also in graphical forms. Own results of mathematical model is then compared to access its validity. After the validation the next important step taken by different automotive researchers is suggestion of control strategy for improvement in the stability of the vehicles. These control strategies are mainly of two types active and passive. Active. Whereas active strategies control the vehicle automatically with online control mechanism like steer by wire, active steering, electronically control system, automated brake system and passive strategies mostly include some kind of indication for the driver to control before Roll over. The most recent passive control strategy is time to Roll over strategy or (TTR). Which give an indication to driver before small span of time and indicate roll over is about to happen. In active systems are incorporated in the vehicle to control roll over. Feed back of different vehicles parameter are measured through sensors and given to control mechanism to avoid roll over. These parameters are mainly steering input, load transfer rate, change in c.g position and lateral acceleration which these input control mechanism which may be electronic or mechanical. Final set of results are obtained after practical implementation of these strategies. Suggestions are made on the basis of these final set of results obtained.

**Development of Model for BPV**

**Case I**

In order to understand the basic mechanics of rollover of a BPV it is necessary to first consider the forces developed in the vehicle on turning while assuming the BPV to be rigid. Whereas by assuming vehicle to be rigid the suspension and tires deflections will not be considered in the analysis. While taking a turn different forces are developed in the vehicle. These forces are not on the same line of action and this difference in line of action produces a moment which tries to roll the vehicle toward the outside of the turn. These forces are shown in the figure-1

**Fig : 1 Forces during roll of BPV**

Following assumptions are made to simplify the model BPV is in steady turn and therefore no roll acceleration, Tire forces shown are representation of the total forces on front and rear of wheels, Vehicle is turn on a cross slope “φ” which is so small that sin φ = φ, cos φ =1. Explanation of different parameters are as under

- Mt  = Total mass of the vehicle
- ay  = Lateral acceleration
- Fiz = vertical force on inner tires on turn
- Foz = vertical force on outer tires on turn
- Fiy = lateral force on inner tires on turn
- Foy = lateral force on outer tires on turn
- H = CG height
- T = Tread
- H1 = distance between roll center and cg
- φ = cross slope

Taking moments about the center of contact for the outside tires yields:

\[ Mt \cdot ay \cdot H - Mt \cdot \phi \cdot H + Fiz \cdot T - Mt \cdot g \cdot T / 2 = 0 \]  
(1)

\[ ay / g = (T / 2 + \phi \cdot H - Fiz \cdot T) / Mt \cdot g \cdot H \]  
(2)
whereas \( M_t = \) total mass of the BPV = \( M_v + M_a = \) mass of the vehicle + mass of the armoring kit

Now a situation specific to BPV is when vehicle is operating in a condition when one side of its tire are burst. BPVs are normally fitted with run flat tires. Run flat tires are special kinds of tires which have a rubberized ring mounted on the inner side of the tire on the rim. In that situation the cross slope “\( \varphi \)” will increase by an amount now \( \varphi_t = \varphi_1 + \varphi_2 \) whereas \( \varphi_1 = \) cross slope of vehicle during turn \( \varphi_2 = \) cross slope resulted after one side of the vehicle is operating on burst tires.

Hence equation 1 and 2 will become will become

\[
M_t ay H - M_t (\varphi_1 + \varphi_2) H + Fiz nT - M_t g T /2 = 0
\]

\[
ay/g = T/2+ (\varphi_1 + \varphi_2) H - Fiz T/ M_t g
\]

\[
\Sigma M_o = M_t ay H - M_t g (T/2 - \varphi (H - H1))
\]

\[
ay/g = T/2+\varphi H
\]

\[
Transfer Ratio
\]

The most common approach used to show roll over tendency is non dimensional parameter load transfer ratio defined as

\[
LTR = \frac{\text{Load on Right Tires} - \text{Load on Left Tires}}{\text{Total Load on All Tires}}
\]

This is achieved by doing torque balance in the roll plane of the vehicle [11]. This parameter changes its value between -1 to 1. Giving 0 value when load on the left and right side are equal. Steady state approximation of LTR can be done using

\[
LTR \approx (2ay/g) (h/T) \]

for small values of roll angle

In a BPV where armoring kit of weight up to several hundred is installed on the vehicle LTR can very effectively give an approximation of roll tendency of the BPV. This armoring kit installation may distribute weight unevenly in the vehicle depending upon the requirement of the user. Protection level may vary from portion to portion in a BPV due to BPV glasses and on one side and extra protection on other side. Extra doors installed in the BPVs in the inner parts also affect this weight distribution. On the same vehicle selected for this purpose which is Land Rover Defender 110. Different scenarios of weight distribution were calculated. In order to study the effect of changing position of cg height this index can very briefly explains the roll behavior of the vehicle. The point where all the load is transferred to the other side of the BPV is considered as the wheel lift position. It is time when roll over has just started. This point should
be dealt very critically in order to understand the stability of the BPV.

**Roll Moment of Inertia**

Roll dynamics of the BPV can also be understood by measuring roll moment of inertia before and after armorning. Whereas BPV is assumed to be homogenous mass and is given by

\[
\text{Roll moment of inertia } [12]= \frac{1}{12} M_t(H^2+T^2)
\]

**Vehicle Parameters**

Computer simulation is based on the calculation of parameters in the equations of motion formulated in the models. Different parameters utilized for this purpose have been either measured or have been calculated on the basis of vehicle parameter databases. Different kinds of information can be extracted from that data which may be the road conditions and maximum allowable speed limits, drivers skill level, social problems and norms, economic stability of the country ultimately linked to condition of vehicles being used and traffic rules implementation. The NHTSA data for inertial parameters have also been utilized. This fact cannot be denied that such kinds of accidents do occur in developing countries which may vary in numbers as compare to NHTSA(National Highway Transport Safety Administration) USA database. According to figures from the NHTSA , SUVs are found to be more prone to rollover as compare to cars. On the basis of that SUV was selected to explain own point of view. Performance of bullet proof vehicles developed in developing countries during riots and gang wars was also considered and Land Rover Defender 110 was selected for this purpose. Different parameters were measured before conversion to BPV. Major parameters measured before bullet proofing of the vehicle were individual weight of each tire of the vehicle , the location of cg, tread of the vehicle. The vehicle was completely disassembled and a armor protection kit for protection against B6 was installed on the vehicle with minimal modification on outer body of the vehicle. The modification in the vehicle included improvised brake system, suspension system and changed sitting arrangement. However same engine of previous vehicle with no modification was utilized in the BPV. Due to change in suspension of the vehicle and increased weight the change in same parameters was measured. This change in parameters related to weight were analyzed in detail. For numerical computing MATLAB has been utilized to have a critical inside view among the two versions of the same vehicle that is before and after armorning.

<table>
<thead>
<tr>
<th>Vehicle characteristic</th>
<th>Land Rover Defender 110</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BPV</td>
</tr>
<tr>
<td>Mass(lbs)</td>
<td>6669</td>
</tr>
<tr>
<td>CG Height(ft)</td>
<td>3.4</td>
</tr>
<tr>
<td>Tread(ft)</td>
<td>4.875</td>
</tr>
<tr>
<td>Roll center Height(ft)</td>
<td>2.8</td>
</tr>
</tbody>
</table>

**Results**

![Effect of CG on roll over thresh hold](image)

**Roll over thresh hold**

Rigid Body Response to Roll angle

![Roll over thresh hold](image)

Rigid Body Response to uneven Roll angle

![Roll over thresh hold](image)
BPV was more prone to roll over. A drastic change in BPV behavior for uneven roll over angle due to sudden load transfer was also observed. The distance between roll centre and CG also revealed an important role in suspended BPV. Load transfer ratio analysis revealed sudden uneven load transfer of BPV if the weight distribution is more above the CG. Although in comparison to BPV with non BPV roll moment of inertia increases with increasing weight but with instable CG height location showed a decreasing trend. Rigid body analysis found to be ineffective to comment on BPV stability. BPV suspended model should include more parameters to critically examine the forces in the vertical plane. Uneven distribution of weight develops certain moments in a BPV which can create hidden instability tendency in a BPV. In future control strategy on the basis of even distribution of weight in a BPV be formulated.

References

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