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Rollover Scenarios in Europe

Abstract

Rollover accidents seem to be a rising problem in Europe and therefore the systematic of this accident scenario should be investigated. Based on statistical investigations on major European accident databases for different countries a series of 73 real world rollover accidents was analysed. These cases were reconstructed using PC-Crash and preliminary categorised using a modified US-based rollover classification. In a first step, the rollover events were reconstructed from the point of conflict to the vehicle's rest position. The vehicles kinematics as well as its linear and rotational velocities were derived. In a second step typical velocity characteristics as well as kinematics were identified and the events categorised according to these criteria. Based on these results four main categories were defined, covering all reconstructed accidents. This categorisation was based on mechanical parameters (rotatory and translatory kinematical data of the vehicle). Significant differences can be seen for different scenarios for the "first phase of rollover".

Notation

Δv change in velocity due to an impact

φ roll angle

$\dot{\varphi}$ roll rate

Introduction

Rollover accidents are one scenario happening to passenger vehicles. This scenario was not investigated on an European level. Investigations mainly in the US have been done on this accident scenario and a classification based on these investigations was derived. For the US classification eight different scenarios are known by ASIC [1], based on typical sequences in the case of rollover. This scenarios are: Trip-over – when the lateral motion of the vehicle is suddenly slowed or stopped inducing a rollover. The opposing force may be produced by a curb, pot-holes, or pavement dug into vehicle wheels. Flip-over – when the vehicle is rotated along its longitudinal axis by a ramp-like object such as a turned down guardrail or the back slope of a ditch. The vehicle may be in yaw when it comes in contact with a ramp-like object. Bounce-over – when a vehicle rebounds off a fixed object and overturns as a consequence. The rollover must occur in close proximity to the object from which it is deflected. Turn-over – when centrifugal forces from a sharp turn or vehicle rotation are resisted by normal surface friction (most common for vehicle with higher centre of gravity (COG)). The surface includes pavement surface and gravel, grass, dirt, etc. There is no furrowing or gouging at the point of impact. Note that if rotation and/or surface friction causes a trip, then the rollover is classified as a turn-over. Fall-over – when the surface on which the vehicle is traversing slopes downward in the direction of movement of the vehicle COG such that the COG becomes outboard of its wheels (Note: The distinction between this code and flip-over includes a negative slope.). Climb-over – when the vehicle climbs up and over a fixed object (e.g. guardrail, barrier) that is high enough to lift the vehicle completely off the ground. The vehicle must roll in the opposite side from which it approached the object. Collision with another vehicle – when an impact with another vehicle causes the rollover. The rollover must be the immediate result of the impact between the vehicles. For example, this could occur at an intersection where a vehicle is struck in the side and the momentum of the struck vehicle results in a rollover. End-over-end – when a vehicle rolls primarily about its lateral axis.

Based on this scenarios it was investigated, if they are applicable for European rollovers too. For choosing real world accidents for in-depth studies, basic studies of the statistics were analysed and resulted with the following characteristics for rollover accidents.

Statistical Analysis

SFERCO et al. [2] found out in the German In-Depth Accident Study (GIDAS) and the Co-operative Crash Injury Study (CCIS) in the UK had shown, that rollover count for 5-15% of all accidents. Single rollover events, without any multiple impact are events in Europe up to 5% of all accidents. This is third of all rollover accidents. For multiple rollover accidents the first event is the impact rather the rollover. So a rollover can be regarded as a consequence of an impact rather than an initiator. Most vehicle rollovers involve one complete roll or less and they occur about the longitudinal axis of the vehicle, approximately half in each direction. When an impact follows an initial roll, it is frequently against a fixed object (rather than a vehicle) and appears to randomly involve all parts of the vehicle. In cases where rollover follows an initial impact, the impacts are split between those against cars and those against fixed objects. A disproportionate number of the initial impacts is against the sides of the vehicle that rolls over (rather than the fronts).

Analysis from the British national accident data (STATS 19) from KIRK [3] showed that 6% of all car casualties were injured in cars with an element of rollover and 12% for killed and severe injured car occupants (KSI). Of all cars that have a fatal occupant or occupants, 15.1% have an element of rollover. For cars that have an element of rollover, accidents that occur whilst negotiating a bend are far more common than for non-rollover cars, although overall normal going ahead accidents are most common. For cars that have an element of rollover, 77% are single vehicle events. For single vehicle crashes from crashes with another vehicle the most commonly vehicle struck is another car. Of all cars, 3.9% that have an injured occupant have a rollover and do not impact another vehicle. For cars with killed and severe injured occupants, frontal impacts are clearly the most common. A higher proportion of vehicles that have an element of rollover leave the carriageway, for KSI cars 81.9%. This also correlates with an increased proportion of objects hitting off the carriageway for cars with an element of rollover, for KSI, 67.7%. An increase in KSI rate is evident when the car leaves the carriageway. For cars with an element of rollover, the most commonly struck object off the carriageway is a tree followed by entering ditches. The most common car rollover accident scenario is for the vehicle not to impact any other vehicle or vehicles and to hit a fixed object off the carriageway and no object in the carriageway, accounting for 45.5% of all vehicles that have any element of rollover and an injured occupant. Of all severity rollover cars, 18.9% have no other vehicle impact or any codeable impact with an object on or off the carriageway.

SFERCO et al. [4] were looking on differences of rollover data for US and Europe and it was shown that rollovers, as a single event (rollovers without the occurrence of any impact) are rare events in Europe. FAY [5] found that rollovers occur more frequently as a part of more complex accident sequences involving multiple impacts. In most of these multiple impact cases, the first event in the sequence is an impact rather than a rollover. In the US, rollovers have been identified as a significant safety issue, because a rollover crash is far more likely to result in fatalities than a non-rollover. Although only 3 percent of all passenger vehicles involved in crashes in 2000 experienced rollover, 20 percent of passenger vehicles involved in fatal crashes rolled. In particular, Sport Utility Vehicles (SUV), Multi Purpose Vehicles (MPV) and other light trucks are over-represented in rollover accidents.

Real World Accidents for In-Depth Studies

For this investigation a database containing about 150 real world passenger vehicle rollover accidents was used. The strategy for choosing these cases for in-depth studies is based on the results of the statistical investigations as well as the quality of documentation of the cases. This cases were reconstructed numerically using the accident reconstruction software tool PC-Crash [6].

Method

Relevant Mechanical Parameters

The PC-Crash reconstruction files of the reconstructions provided mechanical data on tire side forces of all four wheels, velocities in x-, y- and z-direction, the roll angle, the roll rate and the angular acceleration as these seemed to be of importance for detecting a rollover. After studying the provided data it seemed promising to further assess the importance of the roll rate for categorisation as it is used in state of the art technologies. For the general analysis it was focused on the roll rate and the roll angle as the relevant parameters.

This focus seemed plausible as a high roll rate at a low roll angle might not lead to a rollover whereas even a low roll rate at a large roll angle with the centre of gravity nearly above the wheels will cause a rollover. There should be a direct interrelation between the parameters roll rate and roll angle and a rollover case.

In-depth Analysis of Relevant Cases

General Analysis from Point of Conflict to End of Rollover

The first step of analysing the PC-Crash data was to plot the roll rate [deg/s] as a function of the roll angle [deg]. As the different rollover cases analysed vary widely in their roll angle, the roll rate – roll angle graphs show very different patterns in the latter stages of the roll. The vehicle behaviour during the rolling phase (i.e. after the initial event) seems to happen at random.

As many graphs showed similarities at lower roll angles, the roll rate – roll angle graphs were plotted from the roll angle at the initial event ($\varphi_{t=0} = 0°$) to a roll angle of $\varphi = 90°$. This range also includes the relevant phase for detecting a possible rollover and for triggering possible safety systems.

When compared, groups of these graphs (φ = 0°K 90°) showed distinctive similarities and could be sorted into categories. The most obvious group is formed by cases with an impact. The graphs show distinctive differences between cases without impact or with impact.

Category 1: Rollover caused by some kind of impact (other vehicle, tree, or other)
The initial roll rate jumps to form a high peak and rapidly decreases afterwards before increasing again at roll angles of approximately 45°. If the impact is preceded by yawing and/or a sideway skid the graph may show a "γ"-form or encircle the centre of the coordinate system before it shows the characteristic mentioned above.

Category 2: Rollover caused by ramp like object (e.g. flat car, guard rail, slope)
The roll rate quickly rises to a high level but does not decrease as significantly afterwards as in category 1. The yaw angle remains at low levels (less than 30°).

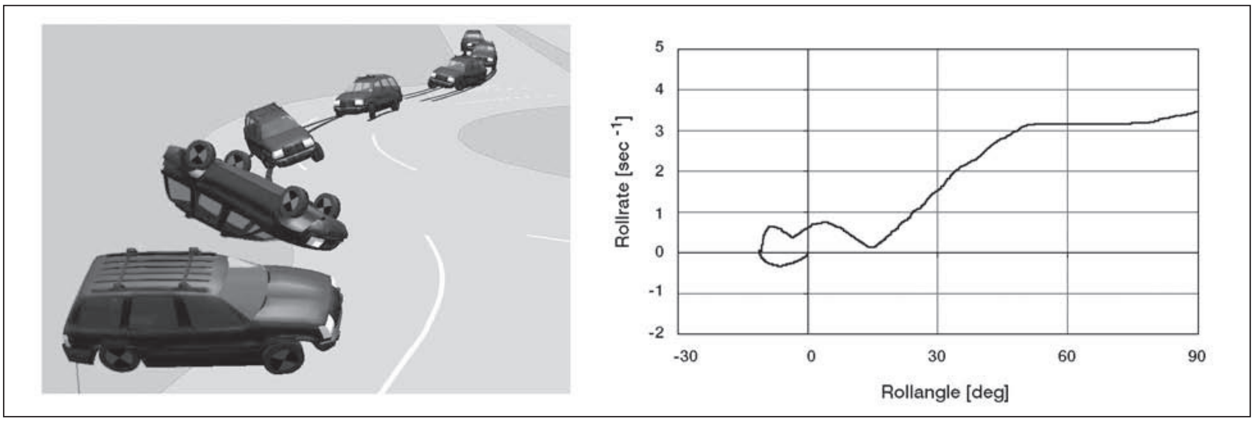

Fig. 1: Example for basic analyse of whole rollover event up to 90° roll angle

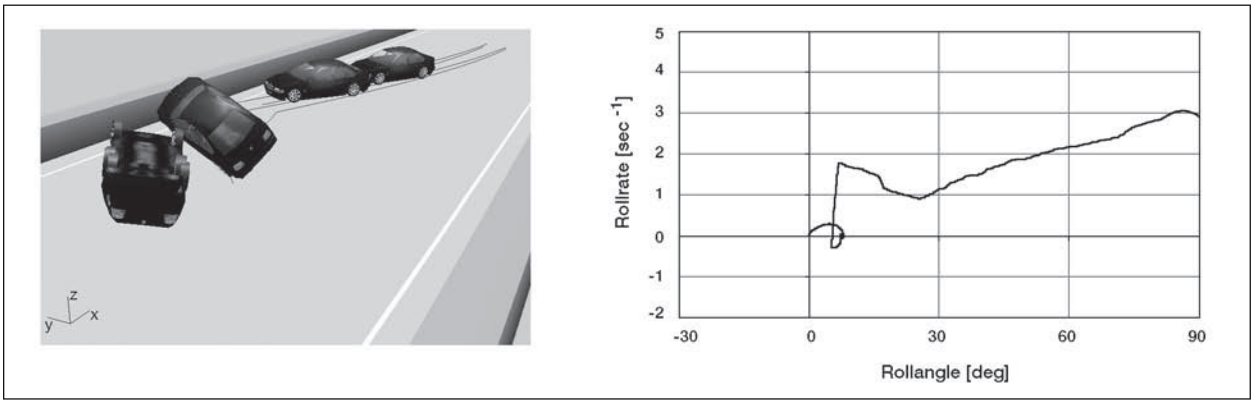

Fig. 2: Example for category 1

Category 3: Rollover caused by yawing and skidding sideways with vehicle being affected by a ditch or slope
The yaw angle at the start of the roll action differs widely (0° to over 200°) but on average seems to be lower than in category 4.

Category 4: Rollover caused by yawing and skidding sideways on an even surface
The roll rate builds up and the roll angle increases a little until it reaches a constant value. The roll rate then decreases again as far as zero deg/s or below. When the vehicle starts to roll the roll rate rises to a high level. The graph shows a picture resembling the Greek letter "γ". Due to strong yawing the graph may encircle the centre of the coordinate system. The increase in the roll rate is slower than in cases with impact. The yaw angle at the start of the roll action is mostly in the range between 70° and 90°.

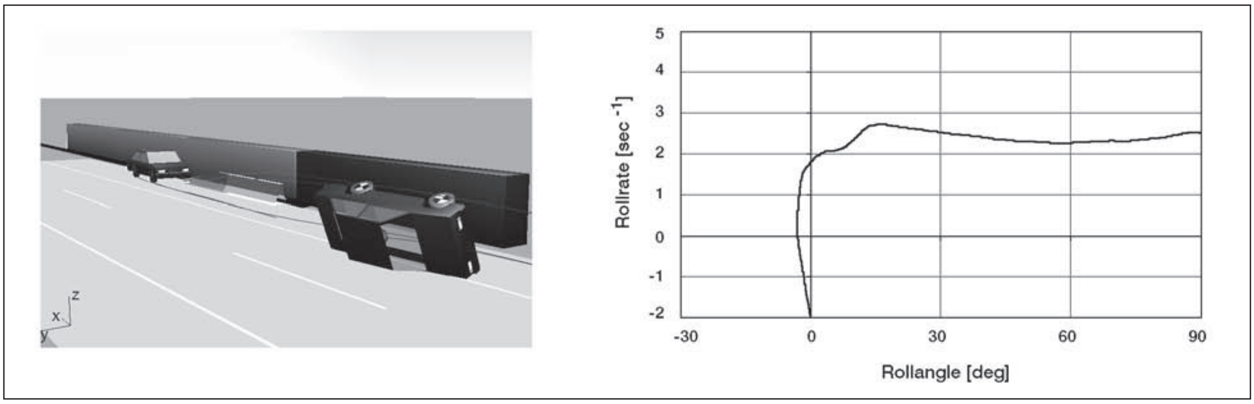

Fig. 3: Example for category 2

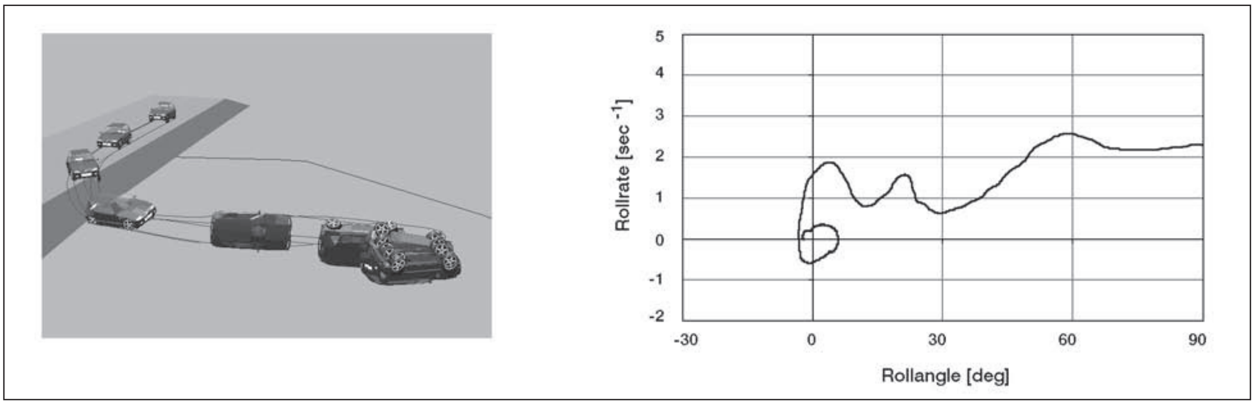

Fig. 4: Example for category 3

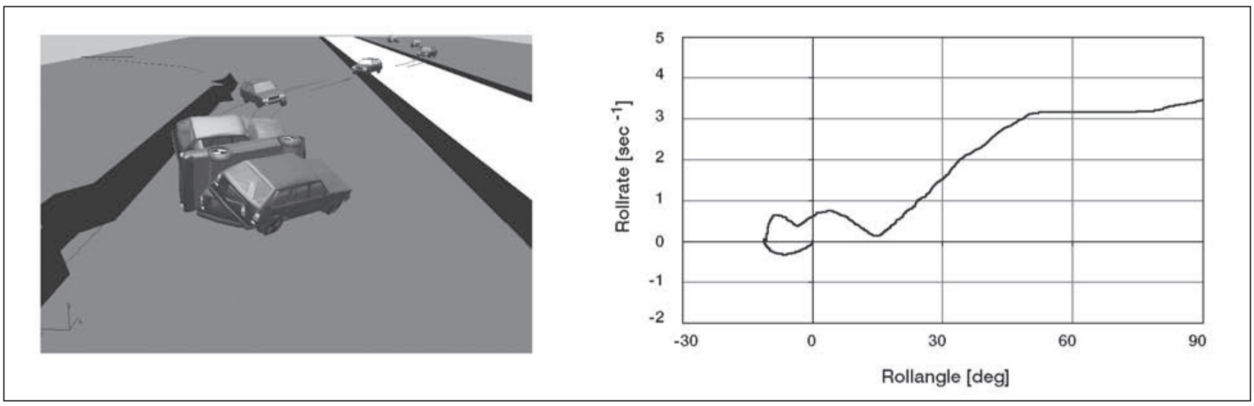

Fig. 5: Example for category 4

Category 5: Rollover caused by other causes
The graphs of pitch-overs show a very different characteristic in the roll rate –¬ roll angle diagram which does not seem to be comparable to the previous cases

In-Depth Analysis for First Phase of Rollover

In a second phase the reconstructed cases were analysed from the start of the rollover (as described below) up to 90 degree roll angle. For this analysis the following time-depending mechanical parameters were available for the reconstructed cases:

Rotational motion: angle, angular velocity and angular acceleration for rolling, yawing and pitching (referenced to centre of gravity in a reference coordinate system)

Linear motion: linear movement, linear velocity and linear acceleration in x-, y-, z-direction (referenced to centre of gravity in a local coordinate system)

Additional: tire forces (side and normal)

For rollovers different parameters were analyzed on their characteristics over the roll angle. The following parameters show the most significant influence for categorisation for the first phase of rollover:

- o Roll rate vs. roll angle
- o Lateral velocity vs. roll angle (in a global coordinate system)
- o Longitudinal velocity vs. roll angle

Due to the long duration of a rollover the characteristic becomes more and more randomized if the whole rolling phase is used. So the rollover is divided into 4 phases (see figure 6):

1. Pre-roll phase
2. Point of no return
3. First phase of roll
4. Rolling phase

Pre-Roll Phase

The pre-roll phase is the phase when the vehicle is coming into a destabilized driving mode till the "point of no return" where the rollover cannot be avoided. In this phase active safety can be used to stabilize the vehicle and avoid exceeding the "point of no return".

The more it seems to be unavoidable to stabilize the car passive safety devices can also be pre-activated in this phase. If possible estimation on the severity of the impending rollover should be done.

Point of no Return

This is not really a time point. It is more a short time interval when the rollover cannot be avoided and passive safety devices have to be activated to reduce the risk of injuries to occupants.

First Phase of Roll

The first phase of roll starts from the "point of no return" and covers approximately the first 90 degrees of roll angle. It ends with the first impact of the vehicle structure with the ground. The car can always be in contact with the ground or loose the contact (flying phase).

Rolling Phase

The rolling phase is the phase from the end of the first phase of roll until the vehicle's rest position. The most important parameter for this phase is the number of turns.

For the detailed analysis of the rollovers the first phase of roll was used and defined in a little

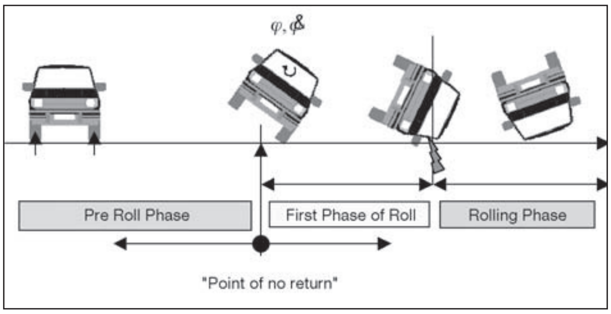

Fig. 6: Phases of a rollover

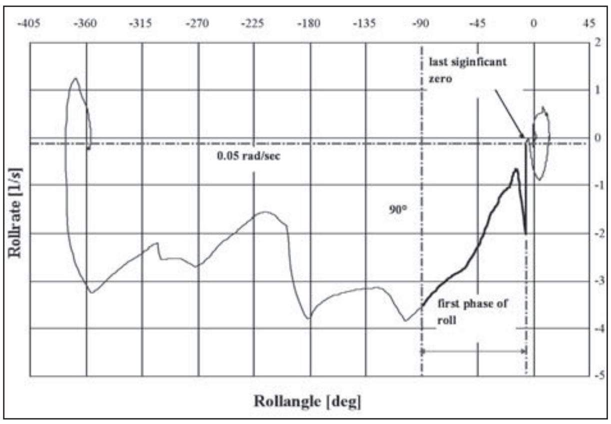

Fig. 7: Determination of first phase of rollover for a 360° left-side rollover

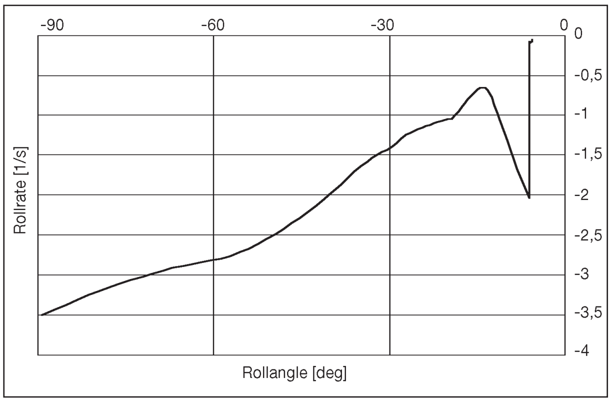

Fig. 8: First phase of rollover for a 360° left-side rollover

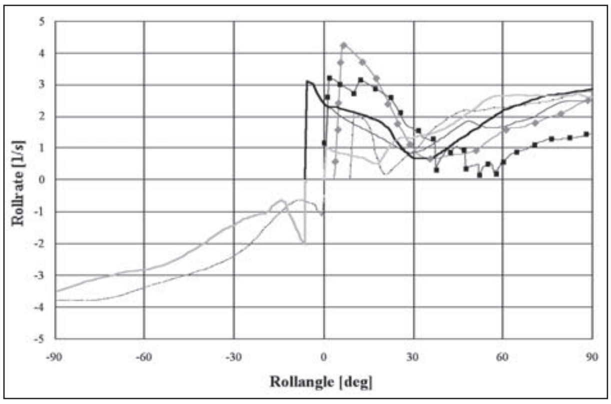

Fig. 9: Characteristics of rollover induced by an impact with Δv <30kph for different real world accidents

modified way. The start of this phase – the point of no return – was defined as last significant zero of the roll rate vs. the roll angle. Due to the numeric data a threshold for the zero of the roll rate of 0.05 rad/sec was used. For the end of the fist phase of roll the 90 degree roll angle criteria was used due to the difficulties in finding the first impact in the rolling phase.

Results

Based on the procedure described all cases were analysed in detail for their significant roll angle – roll rate behaviour for the first phase of rollover. Also the longitudinal and lateral velocity characteristics were investigated and the following results were gained.

The main rollovers can be classified by the following categories:

- Impact induced rollovers
  - Δv <30kph
  - Δv >30kph
- Ramp-like object induced rollovers
- Skidding and Yawing
  - Trip induced rollover
  - Turning and rollover
- Others

Impact Induced Rollovers

Rollover accidents induced by any kind of impact (mostly with another vehicle but also with other object). This type of rollover scenario is divided into tow sub-categories depending on the change of velocity (Δv) during the impact. For high Δv values the impact inducing the rollover is considered as more harmful event than the following rollover.

Δv < 30kph

For this scenario the Δv for the rolling vehicle is less than 30kph. This is based on the analysis of the real world accidents. figure 9 shows the characteristics for this type of rollover. The initial roll rate jumps to form a high peak caused by the initial impact. For increasing roll-angles the roll-rate decreases fast and then increases moderate.

delta v>30kph

Rollover accidents with an Δv higher than 30kph are considered to have a severe front or side impact. Therefore it is necessary to activate the passive safety system for this kind of impact. The following rollover is not as harmful as the initial impact.

Ramp-like Object Induced Rollovers

This type of rollover is induced by any kind of ramp-like object. This could be a guardrail, the end of a concrete barrier as well as an embankment, slope or the hood of an opposite car acts like a ramp. As can be seen in figure 10 the roll rate rises quickly to a high level and stays nearly constant for the increasing roll-angle. The analyse shows also that the longitudinal velocity is high and the lateral velocity is on a low level.

Skidding and Yawing - Trip Induced Rollover

This scenario happens when a car is tripping e.g. the tires are digging into gravel or soil. This is equal to a higher friction acting in the tire-ground contact and therefore a higher lateral force can be

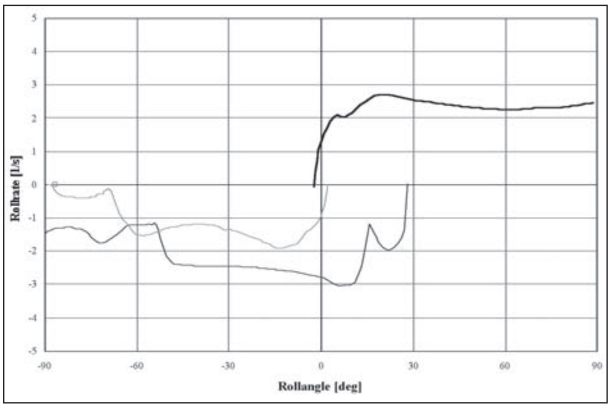

Fig. 10: Characteristics of rollover induced by ramp-like object

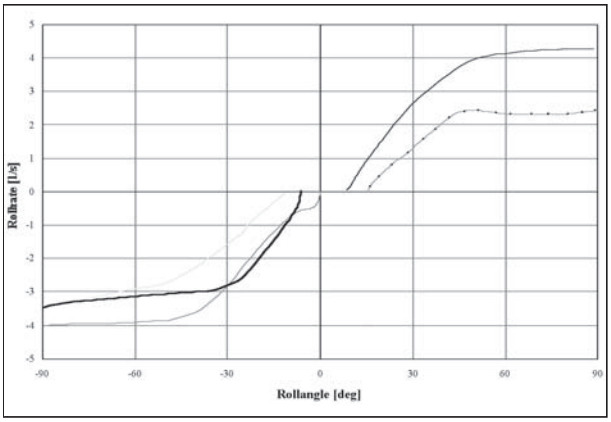

Fig. 11: Characteristics of a rollover induced by tripping

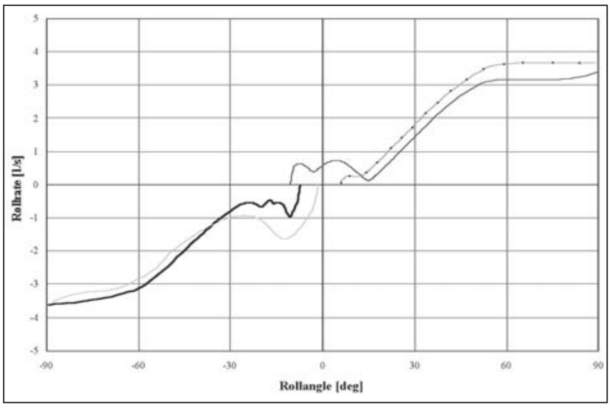

Fig. 12: Characteristics of a rollover induced by turning

obtained. figure 11 shows that the roll rate increase moderate to a constant value. The longitudinal velocity decreases to a constant value and the lateral velocity decreases rapid to a constant value.

Skidding and Yawing - Turning and Rollover

In this type of rollover the vehicle is normally driven on a ordinary surface. Due to the driven manoeuvres and the dynamic characteristics of the vehicle the car gets into a unstable mode and a rollover results. The friction in the tire-ground contact is not increased as in case of tripping. Figure 12 shows that there is a significant initial oscillation in roll-rate caused by the unstable driving mode. The all over behaviour is the same like in case of a tripped rollover.

Others/Special Others

For the remaining rollovers its not easy to categorize them particularly as they are very rare events e.g. the end-over-end rollover, where the roll-axis is lateral. Some other special cases are the free fall of a vehicle e.g. down from a bridge or cases where the car is yawing and the back of the car is tripped when contacting the soil on the road side.

Discussion

The rollover cases chosen for reconstruction represent the statistical results from the survey laid out in the introduction as follows:

According to the STATS 19 77.3% of all rollovers are single vehicle events. From the 73 reconstructed cases 59 (81%) were single vehicle event cases which is the same proportion as found out by SFERCO et al. [2] and KIRK [3]. 43% of the reconstructed cases have an initial impact before the rollover which is a little less than FAY's [5] (58%) findings. In 12 reconstructed cases (16%) the vehicle impacts an object off the carriageway. According to KIRK this proportion is 46%.

In most rollover cases the vehicle turns around its longitudinal axis and makes 4/4 turns or less. The proportion of rolls to the right or to the left is half/half. Accordingly, of the reconstructed cases only 5 vehicles (7%) turned around their lateral axis. Of the others 49 vehicles turned 4/4 or less (67%). In 16 cases (22%) the vehicles turned more than one turn (5/4 to 30/4). For 7 cases it was not possible to account for the number of turns around the longitudinal axis as they were either pitch-overs or the reconstruction file did not give enough information. Of the vehicles turning around their longitudinal axis 32 turned to the right and 31 to the left.

According to GIDAS and CCIS analysis by SFERCO et al. [2] only around one third of all rollovers occur as single, isolated events in the UK and Germany. The remainders occur during more complex multiple impact crash sequences. 43 of the reconstructed cases had no impact and can be regarded as single isolated events. This proportion (59%) is about twice as high as stated by Ford.

Conclusions

The rollover categorisation defined in this work can be used also by non-professional analysts for pre-categorisation of an accident. The rollover can be compared easily to the four main categories: impact induced, ramp-like object induced, skidding and yawing or others. When reconstructing a real world accident a final classification can be done when analysing the vehicle trajectory and its kinematical data. The selected real world accidents represent the statistical findings from other authors.

Ackowledgement

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