INVESTIGATING HEAVY VEHICLE ROLLOVER CRASHES AND THE INFLUENCE OF ROAD DESIGN BY USE OF VEHICLE SIMULATIONS – A CASE STUDY IN NORWAY

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Abstract

A heavy goods vehicle (HGV) overturned at an entry ramp to the E6 freeway in Norway. The 24 m long vehicle combination was a heavy truck & drawbar trailer, legally loaded with timber logs into 57 ton gross vehicle weight. The crash investigation showed that the HGV was stable and that the driver had adjusted the speed in order to merge with the E6 traffic. Simulations were made of the crashed vehicle´s dynamics when driving a 3D model of the entry ramp. The results showed that the entry ramp had a very unfortunate geometry. The crash came as result of a failure in the interaction between the driver and the heavy goods vehicle's performance in relation to the condition and function of the road. The investigation found that the Norwegian Public Road Administration (NPRA) requirements of the design and of construction of entry ramps do not take adequate account of the road's function, i.e. that large heavy vehicles will use the entry ramp. The Accident Investigation Board Norway recommended that the NPRA revise its requirements for design and execution of entry ramps. This case is an example of the large potential for benefits from simulations of vehicle dynamics in crash investigations. A future application may also be validation of safety for road designs. Traditionally road design codes are dealing with one factor at a time. Simulations make it possible to verify safe road designs in 3D, such as crossfall/curvature in combination with downhill grade. Furthermore, vehicle simulations can provide accurate input to projects that identify hazardous existing curves and make decisions on enhanced speed & attention management.

Keywords: Heavy Vehicle Dynamics, Rollover Crashes, Vehicle Simulations, Geometric Design of Roads, Crash Investigation, Curve Speed and Attention Management.

1. Background

A Swedish HGV-trailer overturned while driving at a low speed (about 50 km/h) on an entry ramp to the E 6 freeway in Norway. When the trailer rolled over, its payload of timber fell off and spread across the southbound lanes and partly into the northbound lanes on the freeway, as seen in the photo in Figure 1. A passenger car on its way in the oncoming overtaking lane did not manage to maneuver out of the way and collided with the timber. Neither the driver of the timber lorry nor the driver of the passenger car was injured in the accident. The Accident Investigation Board Norway (AIBN) regards the accident as serious, because it had a high injury/damage potential as the timber on the drawbar trailer spilled across lanes in both directions of the E6 freeway. The speed limit was 100 km/h (today 110 km/h) and there is intense traffic on the freeway. The E6 is part of the Trans European Network - Transportation (TEN-T) road network. All TEN-T roads are covered by an enhanced European legislation for road safety, since the whole TEN-T network has an important function in relation to the traffic flow for all types of vehicles.

The investigation showed that the actual HGV combination had good rollover stability and the velocity data record showed that the driver had adjusted speed to merge with other traffic on the E6. The geometry of the entry ramp had an unfortunate bend, with the tightest horizontal radius at the very end of the ramp, right before the start of the acceleration field. The accident was eventually deemed a result of a failure in the interaction between the driver and the heavy goods vehicle's performance in relation to the condition and function of the road.

Figure 1 The Rollover Crash at the E6 Entry From Svinesundparken. Photo: Stein Johnsen

The investigation also showed that the Norwegian Public Roads Administration's (NPRA) requirements of the design and execution of entry ramps do not take adequate account of the road's function, i.e. that the entry ramp will also be used by large and heavy vehicles. There are no minimum requirements for the entry ramps' geometric values or for assessing the extent to which the entry ramps' geometric design takes into account the dynamic properties of HGVs. The Accident Investigation Board Norway (AIBN) therefore recommended that the NPRA revise its requirements in relation to the design and execution of entry ramps; see AIBN report 2015/06 for details. Road design codes also in other countries may exhibit similar lack of consideration of dynamic properties of HGVs.

2. Research Objective and Aim

The Accident Investigation Board Norway (AIBN) is a public body of inquiry. The purpose of AIBN investigations is to clarify the sequence of events and factors which are assumed to be of importance for the prevention of transport accidents. The AIBN shall not apportion blame or liability.

AIBN itself determines the scope of the investigations to be undertaken. This includes evaluation of the investigations expected safety benefits as compared to required resources. Conclusions and recommendations are always connected to the actual incident. Causal factors can be connected directly to the event, or to underlying factors in organisations, framework and legislations.

This paper aims to present the rollover case as demonstration of the large potential for benefits from simulations of vehicle dynamics in crash investigations.

Another future application for simulations of vehicle dynamics may be validation of safety for road designs, before the road is constructed or reconstructed. Traditionally, road design codes are “dealing with one factor at a time”. Modern simulations make it possible to verify safe road designs in full 3D, such as vehicle response to crossfall and curvature in combination with downhill grade as well as split friction with lower friction in the near roadside wheel path. Furthermore, vehicle simulations can provide accurate input to projects that identify hazardous existing curves and make decisions on enhanced speed & attention management, such as raising “Your Speed” variable message signs.

2.1 Research Approaches

AIBN contracted WSP Sweden for:

- laser scanning the geometry of the crash ramp and the condition of its pavement,
- comparing national road design codes for entrance ramps to freeways in Norway and Sweden,
- assessing the rollover stability of the crashed vehicle, and
- making computer simulations of the heavy truck & drawbar trailer driving the crash ramp, using data from the trucks´ speed log and data on the truck and trailer characteristics.

WSP collaborated with Australian company Advantia Transport Consulting on the vehicle dynamics analysis. The TruckSim® commercial software was used in the analysis.

3. Results

3.1 Road Properties

An overview in bird´s perspective of the crash scene and the assessed turning manoeuvre is given in Figure 2.

The geometry and condition of the ramp was scanned with a Greenwood high speed laser/inertial Profilograph. The Profilograph accuracy is periodically controlled by third party. The system was calibrated immidiately before the measurement, and a control immidiately after the measurement confirmed that no significant change had occurred. The ramp was measured 8 times, and the repeatability between the measured data was found very high.

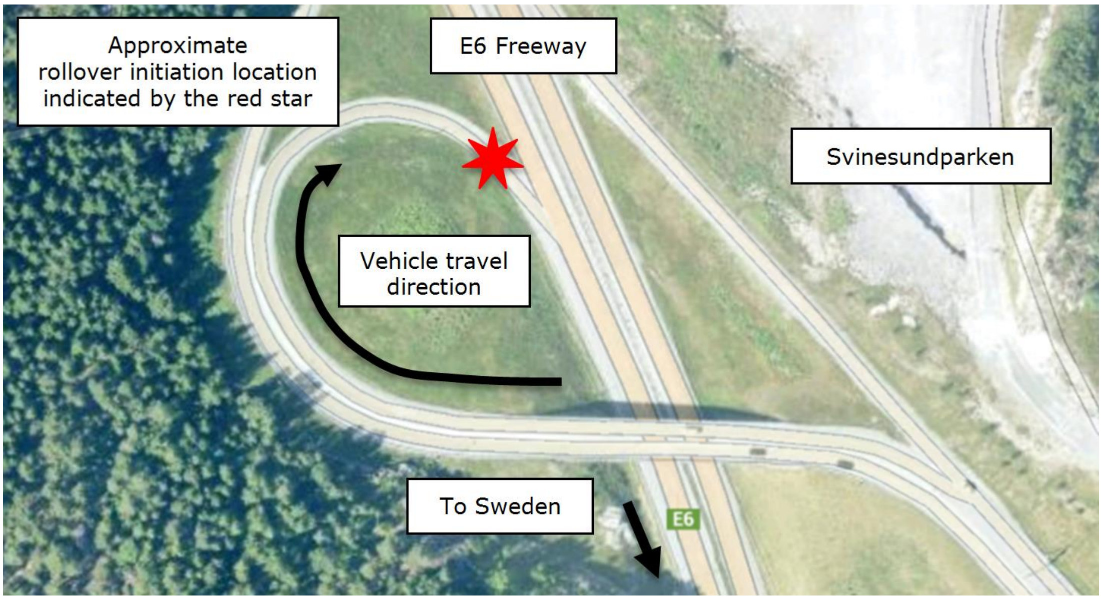

Figure 2 Turning Manoeuvre Assessed

The simulation, see below, showed that the HGV inner wheel lifted from the pavement at Profilograph distance 300 m. The rollover event was initiated earlier, at distance 270 á 280 m.

The ramp is remarkably much inclined down to the freeway. Profilograph data show that the longitudinal gradient of the lane goes down to -10.4 % at the steepest section, located at about distance 260 m.

The early and wider curved part of the ramp has a magnitude for horizontal curvature of -17.7 m^{-1}, corresponding to a curve radius of -56 m (see graph in Figure 3 at distance 200 - 240 m). The tightest curved part of the entry ramp is up to -27.2 m^{-1}, which corresponds to a very sharp curve radius of only -36 m (see distance 260 - 280 m). The cornering lateral force is proportional to the curvature. Hence the lateral force increases by 54 % within 20 m along the ramp, which corresponds to less than 1.5 second of driving at 50 km/h. As seen already in birds view in Figure 2, the ramp curvature is “egg-shaped”. The flatter curvature of the first half of the bend may confuse vehicle drivers to overestimate the maximum safe cornering speed, when approaching the sharper second half of the curve.

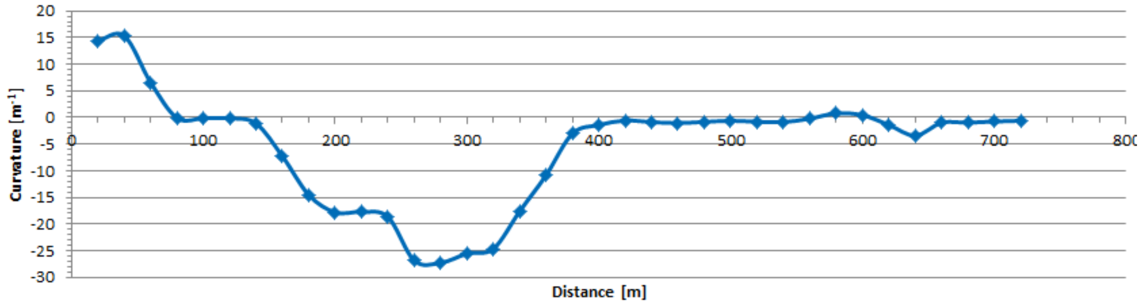

Figure 3 Horizontal Curvature

The pavement crossfall of the lane varies all through the entry ramp, see Figure 4. The maximum crossfall is as steep as -14.6 %, see distance 320 m. The rollover was initiated at distance 250 a´ 260 m, where crossfall - despite sharp and tightening curve radius - is only about -5 á -6 %. At the final rollover section, distance 300 m, the crossfall is -12.6 %.
Note: Norway has right-hand traffic, and negative crossfall indicates that the pavement surface slopes down to the right, from the driver's perspective.

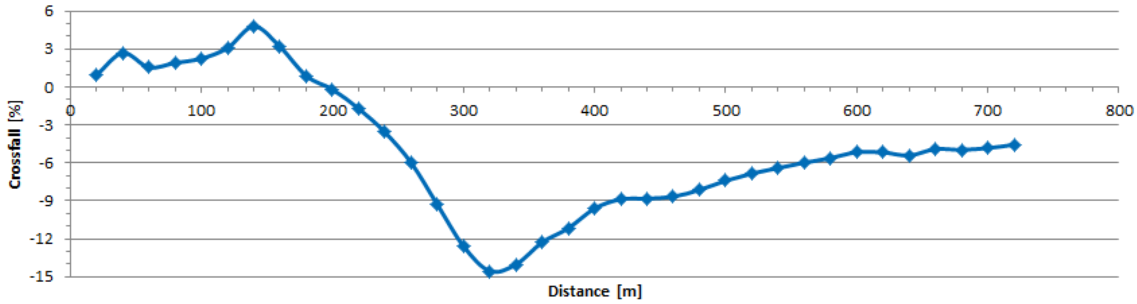

Figure 4 Crossfall

Granlund et al (2014) showed that heavy vehicles, particularly trailers, require much more crossfall to reduce rollover risk in curves, than reflected by traditional road design standards. The influence on rollover risk by curvature and crossfall can be studied with formula 6 from Granlund et al (2014). For this case with velocity 49 km/h (13.6 m/s) and curve radius -36 m, such a study show that the critical Center-of-Gravity height of the trailer increase from only 1.66 m to over 2.0 m when crossfall is increased from -6.0 % (such as distance 260 m in Figure 4) to -12.6 % (see distance 300 m). Therefore, the rollover risk would have been significantly lower with larger crossfall earlier in the curved part of the ramp. Granlund (2016) also highlights that HGV´s call for higher crossfall when a curve is located at a (down-)grade.

The pavement condition was in fairly good condition. Road roughness was low and judged as not contributing factors to the crash. International Roughness Index (IRI) was about 1.0 mm/m (peak 2.3 mm/m) averaged over 20 m. The rut depth was about 6 mm and down to 10 mm at the most. The asphalt pavement had normal macrotexture and was dry at the time of the crash.

3.2 Vehicle and Rollover Event Details

The vehicle was a truck and drawbar trailer combination designed to carry logs. It comprised a Scania R560LB 6x4 truck, and a four-axle trailer, as shown in Figure 5. This a very common vehicle configuration in the Nordic countries.
Note: The truck´s rear-mounted log crane is not showed in the figure.

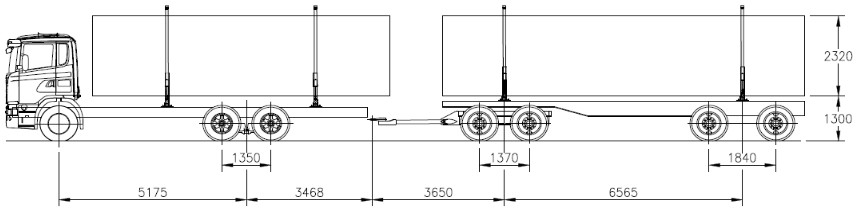

Figure 5 Vehicle Dimensions [mm]

The process of configuring models for vehicle dynamics simulation requires all relevant parameters to be defined. This includes the mass, dimensions, and detailed specifications such as suspension kinematics and compliance, and tyre force and moment characteristics.
The trailer was fitted with BPW axles and mechanical suspension supplied by the Finnish manufacturer Jyki OY. The suspension is similar in design and performance to BPW's 3 leaf (3x22x100) mechanical suspension. The trailer was fitted with 265/70R22.5 dual tyres. These parameters were captured in the vehicle simulation model.

Truck and trailer tare mass data were obtained from the vehicle's registration documents. The mass of the payload carried by the truck and trailer was traced by AIBN. This data is shown in Table 1.

Table 1 Vehicle Mass

Unit	Tare (t)	Payload (t)	Gross (t)
Truck	12.07	10.00	22.07
Trailer	6.60	28.30	34.90
Total	**18.67**	**38.30**	**56.97**

Telematics data of the travel speed of the vehicle for a 60-second period including the rollover event was provided by AIBN. The vehicle was accelerating to merge with E6 traffic, but velocity fell abruptly at the point at which the rollover event is presumed to have occurred. The vehicle was travelling at 49 km/h at that point.

3.3 Analysis of Vehicle Dynamics

Rollover stability was investigated using the Static Rollover Threshold (SRT) measure defined in Australia's Performance Based Standards (PBS) heavy vehicle regulatory scheme.
Australia's PBS scheme requires a minimum SRT of 0.35 g (or 0.40 g for buses and road tankers hauling dangerous goods in bulk). Given that the Nordic countries not yet use any

minimum SRT requirement for vehicles, a value of 0.35 g was considered as reference for a minimum safe level in this instance.

The test method chosen to assess SRT involved a simulated "tilt table". An image of a truck on the tilt table in the simulation environment is shown in Figure 6. The simulation showed SRT = 0.46 g for the truck and SRT = 0.40 g for the trailer. These are good results, and the trailers 0.40 g is much higher than the reference 0.35 g SRT, indicating that the vehicle combination has an acceptable level of rollover stability.

Figure 6 TruckSim® Model of a Vehicle Combination on Tilt Table

For the rollover reconstruction, the vehicle's speed profile was defined from telematics data logged in the truck. The approximate crash location was used as a reference point to align the speed profile with the road data in the simulation environment. The vehicle was made to travel along the defined path using the speed profile, and the outcome was recorded.

For the safe speed assessment, the vehicle was made to travel at constant speed along the defined path. The maximum safe speed was determined using an iterative approach where the vehicle speed was increased until the target level of (in-)stability was reached.

Lowest acceptable stability was defined using the measure "Load Transfer Ratio" (LTR). LTR is a measure of how much of the truck's weight has shifted from the tyres on one side, to the tyres on the other side. OECD/ITF (2010) and TERNZ (2002) reports international experience on the relationship between LTR and crash risk. In this investigation, LTR was considered acceptable if it does not substantially exceed 0.6 during a normal on-road manoeuvre. LTR 0.6 means that 60 % of the inner wheel´s weight is transferred to the outer wheel.

Figure 7 shows a plot of the trailer LTR for the rollover reconstruction, using the recorded speed profile. The trailer LTR is shown because it is the least stable unit in the combination (SRT = 0.40 g), and it was the first unit to overturn in the reconstruction (i.e. LTR of 1.0; 100 % weight transfer to outer wheel). This finding confirms that the recorded speed of 49 km/h was too high for this particular situation.

The maximum speed for the freeway access ramp in order for the truck-trailer to maintain an acceptable level of rollover stability was found to be as low as 33 km/h. A plot of the trailer's LTR for this travel speed is also shown in Figure 7. At this speed, the vehicle's LTR does not exceed the safe level of 0.6.

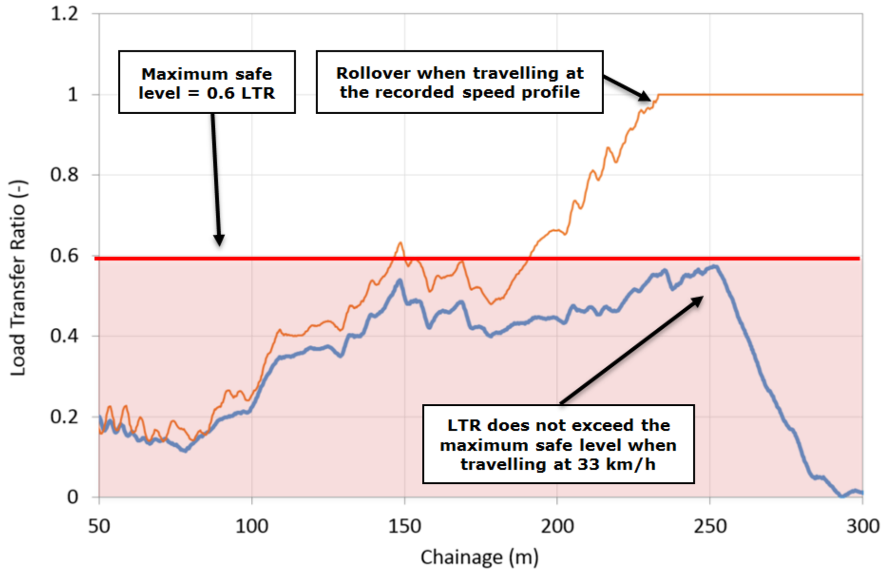

Figure 7 LTR versus Chainage: Rollover Reconstruction Using the Recorded Speed Profile, and Maximum Safe Speed (33 km/h)

An image of the vehicle model negotiating the path in the simulation environment is shown in Figure 8. The screenshot is taken when the trailer rollover passes its point of no return, when driving at 49 km/h. It is important to note that the simulation environment is not intended to be a faithful re-creation of the entire layout of the vehicle and the freeway access ramp. Only the elements of the vehicle and of the road geometry that influence vehicle dynamics (i.e. the curvature, grade, and crossfall of the road) are included, while factors such as vehicle colour and road marking type are default. Hence, the visual output of the simulation (Figure 8) shows only the geometry (i.e. curvature, grade, and crossfall) of the path.

Figure 8 The Trailer Overturned at 49 km/h in the Entry Ramp

The simulation could be configured with different levels of friction for cornering and braking, plus an overall friction limit. The asphalt pavement was dry at the time of the crash. Hence typical values were used for the cornering and braking friction, and a total friction coefficient value of 0.8 was applied.

4. Conclusions and recommendations

The observed rollover outcome was replicated, and the maximum safe speed was determined of 33 km/h for the vehicle combination (rather: the trailer) negotiating the access ramp. The recorded speed profile of up to 49 km/h was too high for the given road geometry and the actual trailer with its payload. The Static Rollover Threshold (SRT) was found to be 0.46 g for the truck, and 0.40 g for the trailer. This is a good result, indicating that both vehicles have acceptable levels of rollover stability. The actual vehicle combination should not be considered to present a rollover risk, provided that it is operated in a safe manner according to the load it carries, the road, and the environmental conditions.

One of the benefits of simulations is that they make it possible to distinct between the role of the driver and the vehicle performance.

The case is an example of the large potential for benefits from simulations of vehicle dynamics in crash investigations.

4.1 AIBN Safety Recommendation ROAD No 2015/09T

The investigation of the timber accident (5 May 2014 on the entry ramp from the Rv 21 road out onto the E 6 road near Svinesund) has revealed that the Norwegian Public Roads Administration's requirements in relation to road design does not take adequate account of the road's function as an entry ramp for heavy and large vehicles. There are no minimum requirements for the entry ramps' geometric values or for assessing the extent to which the entry ramps' geometric design takes into account the dynamic properties of heavy vehicles.

The Accident Investigation Board Norway advises that the Norwegian Public Roads Administration review its requirements in relation to the design and execution of entry ramps in light of the function of the stretch of road for large and heavy vehicles.

4.2 Vehicle Simulations for Validation of Safety for Road Designs

A future application of vehicle simulations may be validation of safety for planned design for new or improved road objects. Traditionally road design codes are dealing with one factor at a time. Simulations make it possible to verify safe road designs in 3D, such as crossfall/curvature in combination with downhill grade. For the purpose of validating safety of road designs, a relevant set of models for reference vehicles are needed. The set of vehicle models may include one or several types of car, SUV, bus, lorry, semitrailer rig, truck with trailer, etc.

4.3 Vehicle Simulations as a Tool for Curve Speed & Attention Management

Another application of vehicle simulations can be to provide accurate input to projects that identify hazardous existing curves and make decisions on enhanced speed & attention management. Such decisions may include the installation of curve warning or advisory speed signs for heavy vehicle drivers approaching entry ramps, exit ramps, roundabouts and sharp curves. For the purpose of curve speed management, a reference HGV such as a rollover-prone trailer with high center-of-gravity can be used.

Attention management actions are particularly appropriate if aspects of the geometry of the road negatively affect vehicle stability (i.e. downgrade, adverse crossfall, high curvature) differ substantially from the overall local standard on the road. The approach of warning signage is in line with both Vision Zero and Safe System methodologies, advising predictability and consistency in the road system.

An example of a heavy vehicle curve advisory speed sign used in Australia is shown in Figure 9, where the recommended safe speed is 20 km/h.

The warning may be further improved by using variable message signs, showing "Your Speed" on a digital display, together with the advised max speed with painted figures.

Figure 9 Australian Advisory Curve Speed Sign for Heavy Vehicles

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