

## ANALYSIS OF HEAVY TRUCK ACCIDENTS WITH REGARD TO YAW AND ROLL INSTABILITY - USING LTCCS DATABASE

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### Abstract

An analysis of heavy truck accidents based on the Large Truck Crash Causation Study (LTCCS) database with respect to loss of control is presented. Heavy truck accidents were analyzed with regard to the accident type, loss of control type, critical maneuver, vehicle combination type and different road characteristics. Three critical maneuvers were identified as the most common maneuvers causing loss of control. The accident analysis results along with existing test maneuvers were used to determine a suitable test for evaluation of yaw stability of heavy trucks on a dry and level road.

**Keywords:** Heavy Trucks, Accident Analysis, Loss of Control, Yaw Instability, Turn-over, Test Maneuver

### Résumé

Une analyse des accidents de poids lourds à partir de la base de données sur les causes d'accidents des poids lourds de grande dimensions - Large Truck Crash Causation Study (LTCCS) – est présentée en se focalisant sur les pertes de contrôle. Les accidents impliquant des poids lourds ont été analysés par type d'accident, de perte de contrôle, de manœuvre critique, de combinaison de véhicules et selon les différentes caractéristiques de la route. Trois manœuvres critiques ont été identifiées comme les causes plus courantes de perte de contrôle. Les résultats de l'analyse des accidents comparés aux essais existants de manœuvres ont été utilisés pour déterminer un essai adapté pour évaluer la stabilité de la trajectoire des poids lourds sur route sèche et plate.

**Mots-clés:** Poids-lourds, analyse d'accidents, perte de contrôle, instabilité de trajectoire, renversement, essais de manœuvres.

## 1. Introduction

Heavy trucks are involved in a significant percentage of severe traffic accidents. According to US statistics, heavy trucks are overrepresented in traffic fatalities; they were involved in 12% of all the fatalities reported in 2004 but accounted for only 7% of total vehicle miles traveled (NHTSA, 2004). In addition to personal injuries and fatalities, heavy truck accidents can result in environmental hazards like spill of cargo. All of these accidents can result in severe financial consequences. There is therefore a strong motivation, from both vehicle safety and financial aspects, to study how these accidents can be prevented.

About 20% of heavy truck accidents are due to loss of control (loss of control refers to yaw instability and turn-over in this paper) which is believed to be significantly reduced by implementation of active safety systems such as ESC, active steering or even further by integrated braking and steering. However, since these systems are still in the development phase and limited in the market, it is impossible to undertake a fleet study to estimate their potential effectiveness. Another approach to address this problem is to evaluate such active safety systems in controlled tests imitating real accidents.

This paper presents a study on heavy truck accidents based on the Large Truck Crash Causation Study (LTCCS) database for determining a number of common maneuvers causing loss of control. Similar studies have been done by other researchers, for instance a study undertaken in the Netherlands (Hoogvelt et al., 1997) showed that 61% of heavy truck rollover crashes could be attributed to speed through curves, 26% are caused by the vehicle running onto the soft shoulder and 10% are related to evasive maneuvers. dePont (2005) found that in Tasmania 16.3% of all heavy truck accidents were rollover accidents, 50% of which were due to speed through curves, 27% due to running off the edge of the roadway, 9% due to vehicle defects, 7% due to load shift and 2% were the result of an evasive maneuver. Both of these studies are focused on rollover accidents of heavy trucks; however the statistical study presented in this paper covers not only rollovers but yaw instability as well. This result along with existing test maneuvers were used to develop a test maneuver for the evaluation of yaw stability of heavy trucks.

## 2. Accident Categorization Method

In order to be able to determine the types and frequencies of accidents which are due to a truck's loss of control, it is first necessary to categorize trucks involved in traffic accidents. In this study, the authors categorized vehicles based on their "Role in Accident". These categories are:

1. Striking vehicle - loss of control
2. Striking vehicle - other than loss of control
3. Struck vehicle

The target population of trucks in this study consisted of those which caused an accident because of a loss of control, in other words trucks which belong to the "Striking vehicle - loss of control" category. Loss of control in this paper refers to:

1. Yaw instability: deviation from driver intended path due to understeer, oversteer, trailer swing or any other yaw motion
2. Turn-over: rollover which is solely due to severe steering maneuver and consequent excessive lateral acceleration (refer to NHTSA rollover types)

Trucks which did not cause the accident (Struck vehicle category) or those which caused it for reasons other than loss of control, such as driver fatigue/inattention or vehicle failure, were excluded from this study.

As mentioned previously the main goal of this study was to determine the most common maneuvers causing loss of control. In this scope real accident scenarios were studied to determine the critical maneuvers which lead to loss of control. The categorization proposed by authors for critical maneuvers is provided in Table 1. Additionally, accident type was also determined for each vehicle to get an overview of the correlation between different accident types and loss of control. The considered accident type categories are given in Table1.

**Table 1** – “Critical Maneuver” and “Accident Type” categories

<b>Critical Maneuver</b>	<b>Accident Type</b>
Negotiating a curve	Single vehicle accidents
Turn at Intersection	Head-on collisions
Avoidance maneuver	Rear-end collisions
Lane change	Sideswipe collisions-same direction
Road edge recovery	Sideswipe collisions-opposite direction
Heavy braking on straight road	Intersection collisions
Avoidance maneuver/lane change in a curve	Collisions with pedestrian/animal
Going fast on a low friction straight road	Other collisions

### 3. Accident Data

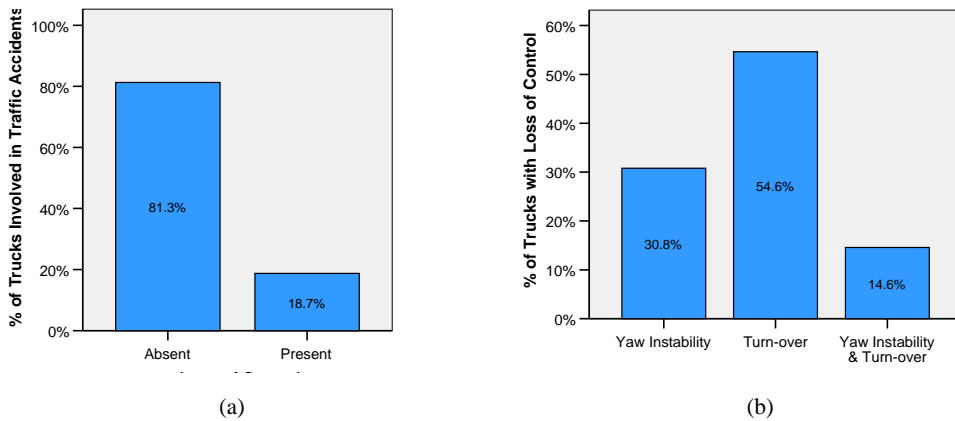
After developing a categorization method, the LTCCS database was used to conduct the statistical analysis. LTCCS is an in-depth database collected by the National Highway Traffic Safety Administration (NHTSA) and the Federal Motor Carrier Safety Administration (FMCSA) of the United States Department of Transportation. LTCCS includes accidents involving at least one heavy truck which caused an identifiable injury.

The crashes that were examined occurred from April 1, 2001, to December 31, 2003. There were 1,070 crashes involving 2,284 vehicles. National estimates were calculated by applying weights to these vehicles and crashes. When the counts from these crashes were weighted, they represent 120,000 crashes involving a total of 241,000 vehicles, of which 141,000 are large trucks (Starnes, 2006).

### 4. Results

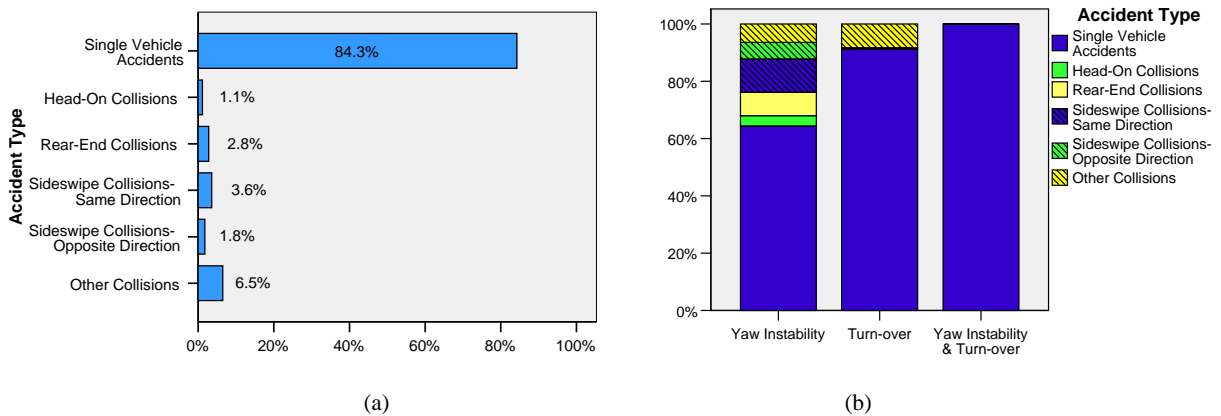
Loss of control accidents were analyzed with respect to the accident type, loss of control type, critical maneuver, vehicle combination type and different road characteristics (such as road surface, road profile and road alignment). The obtained results are provided in this section.

As shown in Figure 1, Loss of control was associated with 18.7% of trucks involved in accidents. 54.6% of these trucks turned-over, 30.8% had yaw instability and 14.6% were attributed to both yaw instability and turn-over.



**Figure 1**– Presence of “Loss of control” for trucks involved in traffic accidents (a)  
Distribution of loss of control types (b)

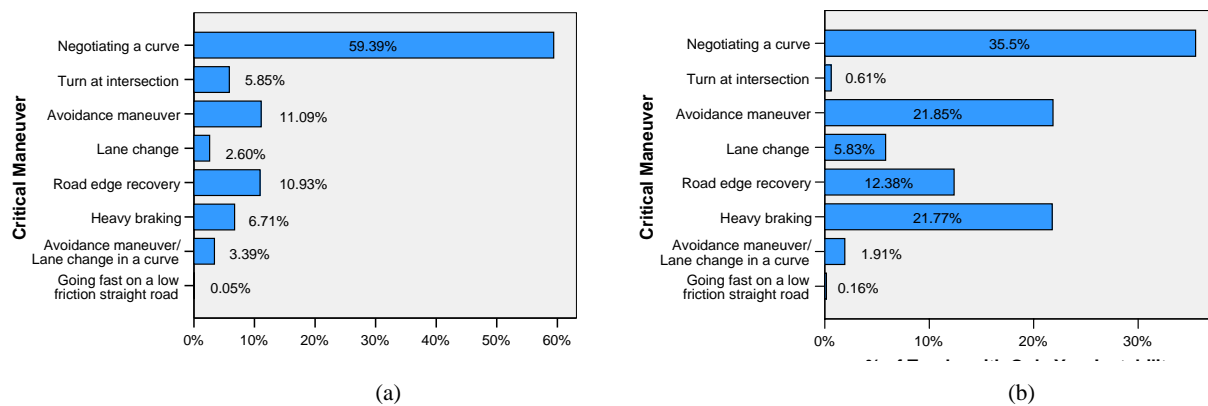
Figure 2a shows the distribution of accident types for the trucks with loss of control, while Figure 2b shows the percentage of different accident types within each loss of control type. In general most of the trucks with loss of control accidents (84.3%) were involved in single vehicle accidents; however, other accident types such as sideswipe and rear-end collisions are associated with a considerable portion (35.6%) of trucks with yaw instability.



**Figure 2**– Accident types for trucks with loss of control (a)  
Accident types within each loss of control type (b)

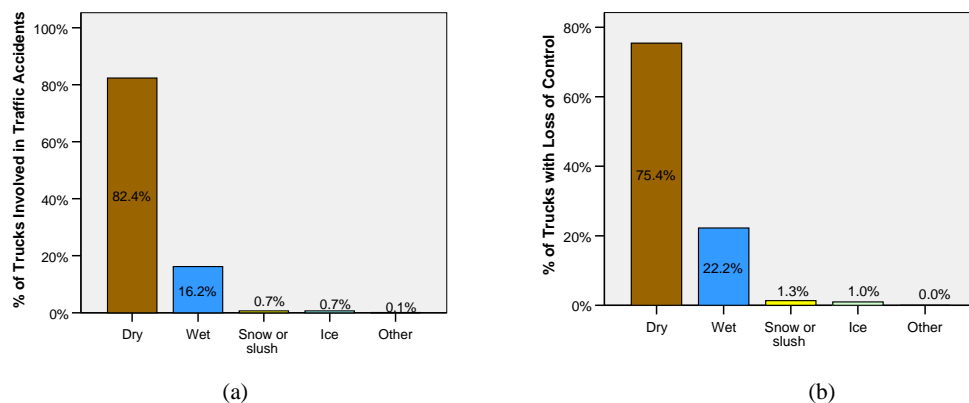
As depicted in Figure 3a, negotiating a curve was the main critical maneuver leading to loss of control (59.4%) followed by avoidance maneuver (11.1%) and road edge recovery (10.9%). When only trucks with yaw instability were considered, negotiating a curve was still the main critical maneuver but with a lower contribution (35.5%), second were avoidance maneuver (21.8%) and heavy braking (21.8%) followed by road edge recovery (12.3%), see Figure 3b.

It should be noted that none of the trucks with heavy braking as the cause of yaw instability, were equipped with ABS and most probably the accident would have been avoided if the trucks were equipped with ABS. On the other hand, ABS will most probably be a standard system for trucks equipped with anti-loss of control systems in future. Hence heavy braking was not considered in the development of the test maneuver for evaluation of yaw stability of heavy trucks, presented in last section.

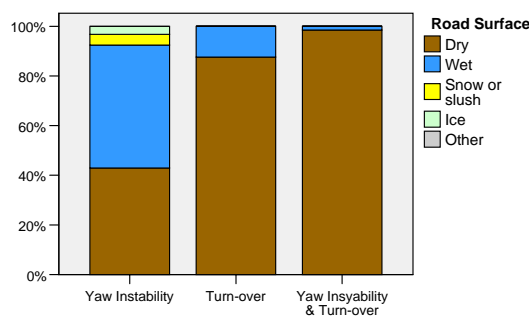


**Figure 3** – Critical maneuver for trucks with loss of control (a)  
Critical maneuver for trucks with only yaw instability (b)

Loss of control accidents were also analyzed with regard to the road condition. A dry road surface was the dominant condition in truck accidents; however the percentage of wet surface condition showed an increase from 16.2 % for all trucks in traffic accidents to 22.2 % for trucks with loss of control. This represents 37% increase which was expected due to the fact that low friction increases the vehicle instability risk, see Figure 4. Furthermore Figure 5 shows that a low friction surface contribute to more than 50% of yaw instability of trucks. Based on this statistics, dry and wet road surfaces should be considered in development of evaluation tests, however snow and ice conditions are not that frequent to demand for a specific test development.

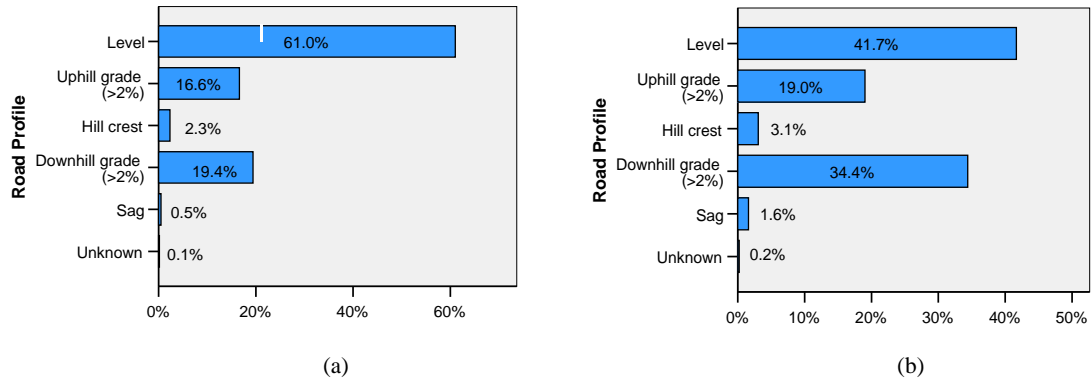


**Figure 4** – Road surface condition for all trucks involved in traffic accidents (a)  
Road surface condition for trucks with loss of control (b)



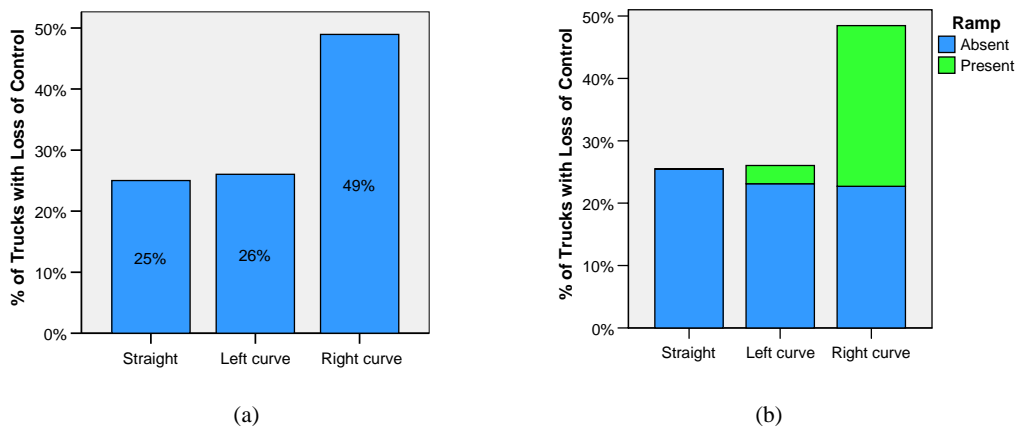
**Figure 5** – Road surface condition for trucks with different loss of control types

According to Figure 6 roads with downhill grade (>2%) are associated with about one third of trucks with loss of control, while this figure for all trucks involved in traffic accidents is only 19.4%. Thus it is advised to consider downhill grade in the evaluation test development.



**Figure 6** – Road profile for all trucks involved in traffic accidents (a)  
Road profile for trucks with loss of control (b)

As shown in Figure 7a, 49% of trucks with loss of control were traveling on a right curved road which is almost double of those (26%) which were traveling on a left curved road. This unexpected difference necessitated further investigation of the accident data. It was found out that many of the trucks underwent a loss of control while traveling on an exit/entrance ramp due to the sharp curve of the ramp and their excessive speed.

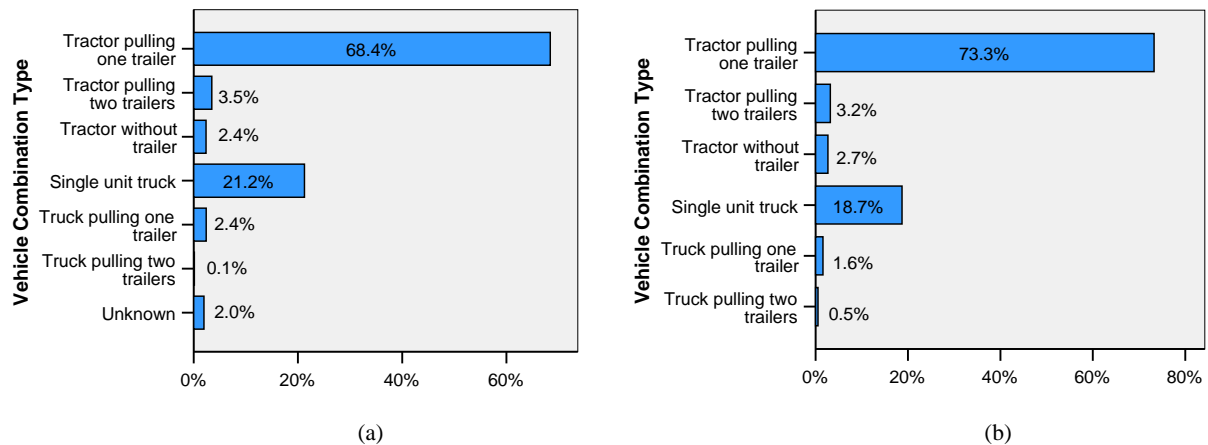


**Figure 7** – Road alignment distribution for trucks with loss of control (a)  
Joint distribution of road alignment and exit/entrance ramp existence (b)

The cross tabulation in Figure 7b shows the joint distribution of the road alignment and existence of a ramp for trucks with loss of control. It can be seen that the distribution of left curve and right curve for trucks traveling on non-ramp roads was almost equal and the distribution difference in Figure 7a is due to trucks traveling on a ramp and the fact that right curved exit/entrance ramps are much more frequent.

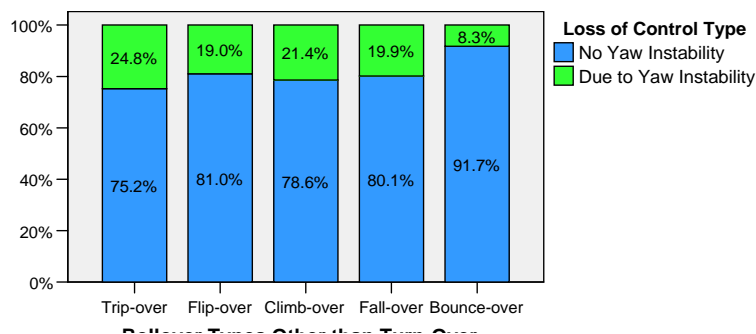
It was sought to investigate whether there are some vehicle combination types more prone to loss of control. Figure 8 shows the combination type distribution over all the trucks involved in traffic accidents and also over the trucks with loss of control. In both cases the most common

combination type is tractor pulling a trailer and is then followed by single unit trucks. There is nothing unexpected in these graphs since these two combination types are the most common types in the US traffic. Unfortunately the authors could not find the combination type distribution for the trucks in traffic in the US to normalize the obtained results.



**Figure 8** – Combination type distribution for all the trucks involved in traffic accidents (a)  
Combination type distribution for the trucks with loss of control (b)

Finally it is worthwhile to address the connection between yaw instability and different rollover types. As previously mentioned loss of control is defined as yaw instability and turn-over in this study. However by dealing with yaw instability a considerable portion of other types of rollover was addressed as well, since they can be consequence of a yaw instability. In fact yaw instability contributes to about 20% of all other types of rollover as presented in Figure 9. For more information about the definition of different rollover types please refer to NHTSA categorization of rollovers (NASS Manual, 2000).



**Figure 9** – Contribution of yaw instability to rollover types other than turn-over

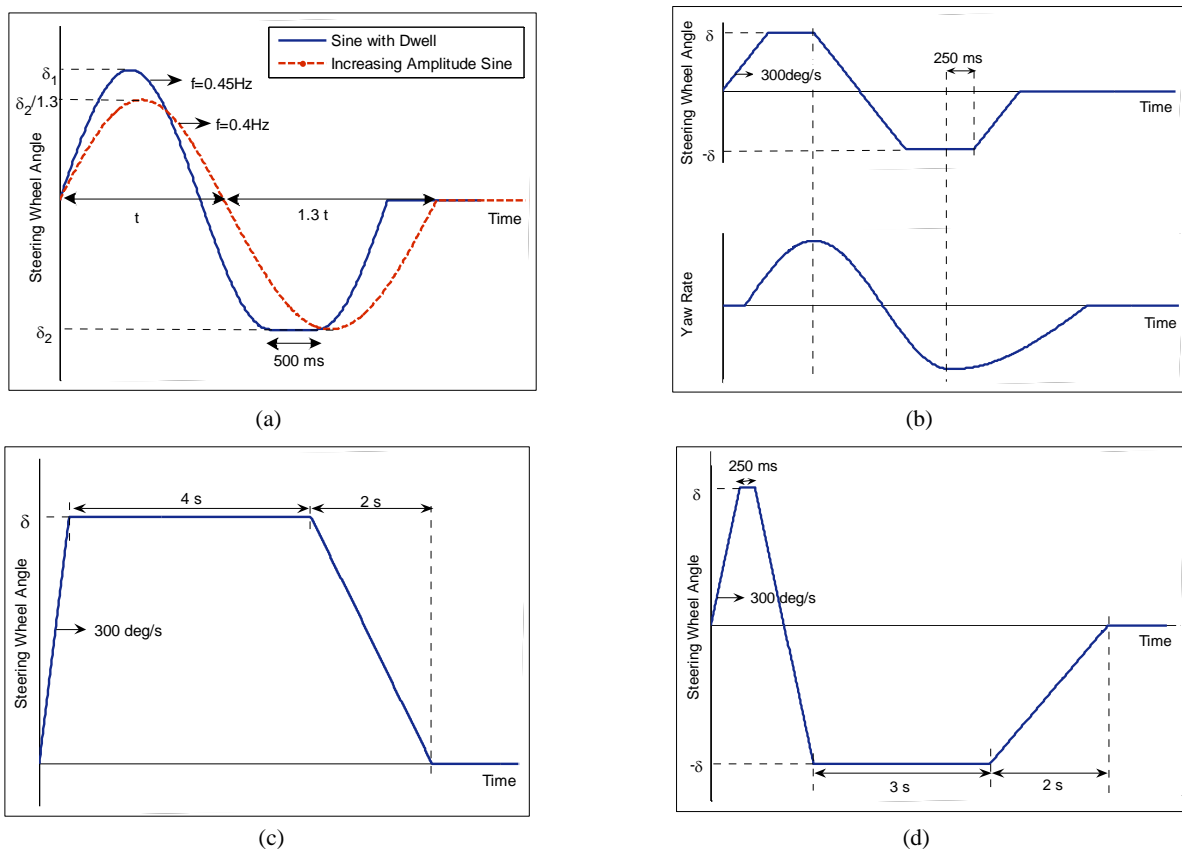
## 5. Test Maneuver for Evaluation of Yaw stability

The focus of this section is on test development for evaluation of yaw stability and the lateral dynamics study of the heavy trucks on a dry and level road. The presented statistics showed that the three most common maneuvers leading to truck yaw instability are: negotiating a curve, avoidance maneuver and road edge recovery. These maneuvers were considered as the basis for test development.

In Table 2, the relevant existing tests addressing the presented critical maneuvers are given. A comparison was made between them to find the most severe and suitable test for study of the lateral dynamics of trucks which can cause high side slip angles and yaw rates. The single/double lane change was excluded from the comparison due to its closed loop nature and dependency on the driver input which reduce its consistency. Although J-turn and Fishhook are widely known as rollover tests; they were included in this comparison to verify their possible utility. A similar experimental study was conducted by NHTSA to develop an Electronic Stability Control (ESC) performance criterion for passenger cars (Forkenbrock et al., 2006).

The test maneuvers, shown in Figure 10, were applied on a 5DOF loaded tractor-trailer model in Matlab-Simulink. The simulation was run with speeds of 50, 60 and 70 km/h and the steering angle used for each maneuver was increased until one of the following was achieved:

1. A side slip angle of 15 deg or more on either of the vehicle units.
2. A 100% Lateral Load Transfer (LLT) which represents a high possibility of turn-over.



**Figure 10** – Sine with dwell & Inc. Amp. Sine (a) YASR with pause (b) J-Turn (c) Fishhook (d)

In order to determine the proper frequency of the Increasing Amplitude Sine (IAS) and Sine with Dwell tests, and the proper steering rate for Yaw Acceleration Steering Reversal (YASR) with pause, their severity and the resulted lateral displacement were compared with different values of frequency or steering rate (as appropriate for the test). The lower the frequency or steering rate, the more severe (higher side slip angle) the condition imposed on the vehicle combination was, so the lowest frequency or steering rate which caused a lateral displacement of about a lane width



(the common displacement of trucks in avoidance maneuvers in real life situations) and not larger displacement was chosen. J-turn and Fishhook tests were simulated with the same steering rate as the YASR with pause. The selected steering input values are given in Table 2.

**Table 2** – Relevant test maneuvers for the aim of this study

Test Maneuver	Emulated Real Life Situation	Selected Steering Rate	Selected Frequency
Sine with dwell	Avoidance maneuver	-	0.45 Hz
Increasing amplitude sine	Avoidance maneuver	-	0.4 Hz
YASR with pause	Avoidance maneuver	300 deg/s	-
Single/double lane change	Avoidance maneuver	-	-
J-Turn	Tight curve road	300 deg/s	-
Fishhook	Road edge recovery	300 deg/s	-

The next step was to determine the proper velocity of the tests. To do so the simulation results with different speeds were compared. In order to achieve high side slip angles at speeds of 50 and 60 km/h, high level of steering input was required which resulted in steering rates beyond the ability of a human driver (about 300 deg/s for trucks). Therefore speed of 70 km/h was chosen for the final comparison of the test maneuvers. The obtained results are given in Table 3.

The sine with dwell test was able to cause a side slip angle of 10.7 deg with a smaller steering angle, 105 deg, in comparison with 120 deg for IAS and YASR with pause; furthermore a greater normalized trailer yaw rate (0.25) was achieved with sine with dwell. As expected J-Turn and Fishhook maneuvers were not capable of producing as high a side slip angle and yaw rate as the other test maneuvers and they would lead to vehicle rollover before achieving it.

A sine with dwell with frequency of 0.4 Hz and speed of 70 km/h was chosen as the most appropriate test for lateral dynamics study of heavy trucks; further studies with different vehicle combination types and loading conditions are required for a more thorough comparison.

**Table 3** – Severity comparison of the test maneuvers at speed of 70 km/h

	Sine with Dwell	Inc. Amp. Sine	YASR with Pause	J-Turn	Fishhook
<b>Max. steering angle before 100% LLT (deg)</b>	105	120	120	90	85
<b>Trailer's side slip angle (deg)</b>	10.7	10.7	10.4	8.3	8.5
<b>Trailer yaw rate, normalized by steering angle</b>	0.25	0.22	0.23	0.22	0.24
<b>Yaw rate rearward amplification<sup>1</sup></b>	1.34	1.28	1.20	1.22	1.27
<b>Off-tracking (m)</b>	1.32	1.33	1.26	1.14	1.14
<b>Tractor lateral displacement (m)</b>	4.3	4.6	4.7	NA	NA

<sup>1</sup> ratio of the yaw rate of the rearmost unit to that at the hauling unit

## 6. Conclusion

An analysis of heavy truck accidents has been conducted to identify common critical maneuvers or other factors causing loss of control. The main findings of the statistical analysis can be summarized as follows:

- Loss of control was associated with 19% of Trucks involved in accidents.
- Turn-over was a more common type of loss of control than yaw instability; the former was associated with 55% of trucks which underwent loss of control, while the latter to 31%, the rest 14% experienced both.
- About 84% of the trucks with loss of control were involved in single vehicle accidents, however other accident types were associated with 35.6% of trucks with yaw instability.
- Negotiating a curve is the main critical maneuver leading to loss of control (59%), followed by avoidance maneuver (11%) and road edge recovery (11%). Considering only trucks with yaw instability, negotiating a curve was still the main critical maneuver but with a lower contribution (35%), second was avoidance maneuver (22%).
- Dry road conditions were present for 75% of all trucks which underwent loss of control; however wet road conditions were associated with more than 50% of trucks with yaw instability.
- Downgrade road (34%) dominates upgrade road (19%) for trucks with loss of control.
- It is not only turn-over which was addressed in this study. Preventing yaw instability of trucks will lead to about 20% reduction of other rollover types.

Based on the accident analysis, a comparison was made between existing test maneuvers to identify the most suitable one for the evaluation of yaw stability of the heavy trucks on a dry and level road. It was concluded from a simulation study that a sine with dwell with frequency of 0.4 Hz and speed of 70 km/h is the most appropriate test and can cause high side slip angles and yaw rates.

## 7. Acknowledgements

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