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# TILTING OF TRUCKS: A DRIVER EDUCATION SYSTEM AND WARNING SYSTEM

R.J.A. Kleuskens
TNO Road Vehicles Research Institute
Vehicle Dynamics Department
The Netherlands
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## ABSTRACT

To reduce the risk of tilting, TNO has developed a tilt warning system for commercial vehicles. This system is able to monitor vehicle weight, lateral acceleration and velocity during normal operation. The system CPU is constantly comparing the measured lateral acceleration to a calculated limit value. It can be connected to a PC, providing the opportunity to on-line or off-line analyze trip data. The system has proven itself as a useful educational and off-line warning tool for commercial vehicle drivers. TNO has patented the system.

## 1. INTRODUCTION

### 1.1 Accident figures

In the last decade the number of tilt accidents of commercial vehicles seemed to have increased very rapidly. In the Netherlands not a day passes where radio traffic information doesn't contain a message of a tilted truck. One explanation is certainly that the press is better informed than 10 years ago, due to an increased and improved information network. Especially when it concerns accidents with trucks carrying dangerous goods, such as chemicals, there will be a nation-wide coverage of the accident, since it is still seen as very dangerous, in spite of the fact that legislation on national and E.C. level is very strict.
Obviously when a truck combination carrying dangerous goods is involved in an accident, the risk for the people and the environment cannot be neglected.

In most situations however, the tilt accidents cause a severe disruption of traffic, leading to a large economical damage. The estimated average loss of money caused by such an accident varies from 100.000 ECU up to 1.000.000 ECU [1]. These figures contain direct damage to vehicle and cargo. Environmental damage, the support costs (police, ambulance, etc.) and economical damage, caused by the traffic jam, and (fatal) injuries are not included. A tilt accident could therefore easily add up to an amount of 10.000.000 ECU.
To obtain an impression of the total amount of money involved, the number of tilt accidents have to be registrated. Here, the actual problem becomes evident. The exact number of tilt accidents in The Netherlands is not known. When exploring the accident statistics, they disappear in the large category of one vehicle accidents. A list was kept of the tilt accidents that were broadcasted via traffic information, causing severe traffic jams. The total number of registrated tilt accidents in one year (july 1993 to july 1994) exceeded 40 (see Figure 1).

Figure 1 Tilt accidents in The Netherlands

### 1.1 Problem solving

#### 1.1.1 *Legislation*

In the past a lot of attention has been paid to the lateral stability of commercial vehicles. Research on this topic is carried out by Ervin, Fancher, Nordström [2] and Sweatman [3]. These activities have not yet lead to an internationally accepted standard, but it improved knowledge concerning the causes of lateral instability. The most concrete guideline, defined by Nordström as well as Sweatman, is the minimum lateral velocity of 4 $m/s^2$ for a fully loaded commercial vehicle.

#### 1.1.2 *ISO*

In the ISO TC22/SC9 WG 6, the primary objective is to determine the lateral stability of heavy commercial vehicle combinations and articulated buses. Under preparation are definitions of characteristic values and functions in time domain and frequency domain which are considered necessary to characterize the transient response of vehicle combinations. The characteristics are rearward amplification of lateral acceleration and yaw velocity, dynamic off-tracking, critical speed for oscillatory instability, yaw damping including mode-shape information.

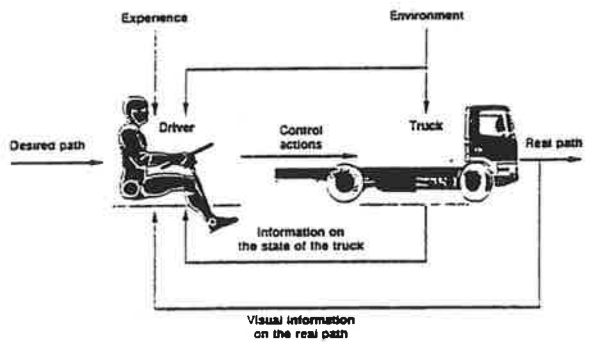


Figure 2 Capabilities, information and effort

#### 1.1.3 *Development*

Commercial vehicle manufacturers pay a lot of attention to the handling capabilities of their vehicles. Handling, as a safety related issue, has become a selling item, beside comfort. Basic to the approach of handling judgement is to split it up over the three aspects, indicated in Figure 2.

**Capability**

The capability of the vehicle means: is the vehicle in itself capable of performing the required manoeuvres, maintaining a sufficient acceptable level of safety?

**Information**

This aspect concerns the information to the driver. The question is whether he receives the accurate, consistent and unbiased information as needed to perform his controlling tasks successfully. This information may be biased by the environment (road conditions, cross-wind, etc.). Here also the experience of the driver is important.

**Effort**

The effort, required by the driver to control his vehicle can be direct (course changes), indirect (corrective effort to keep course) and ambient (the fatiguing effect of vehicle movement, bad information etc.). These three aspects need to be accounted for in the assessment of criteria for safe vehicle handling.

By this fundamental approach maximum insight is gained in what, in the end, determines the handling qualities of a commercial vehicle. This approach allows for a clear distinction between characteristics which concern the vehicle alone and characteristics which concern the vehicle driver interface.

Problems with lateral stability of commercial vehicles occur when the driver is not aware of the actual condition of his vehicle, which might be close to its limits (no information, therefore getting the impression there is no danger (straight ahead stability) or overrating the vehicle (cornering)). By improving the information flow of vehicle status to the driver this danger could be diminished.
For commercial vehicles, with a large difference between laden and unladen situation resulting in a completely change of behaviour, this aspect is very important. Therefore, improvement of information flow has become a design objective.

#### 1.1.4 *Others*

One other possibility to avoid tilt accidents of commercial vehicles is to improve the education of truck drivers. If the driver is aware of the capabilities of his vehicle and knows what he should do in dangerous situations this could help in avoid or at least diminish the results of an accident.

## 2. THE TILT WARNING SYSTEM

To provide in a tool that can help in educating and warning the driver, TNO has developed a system that monitors the vehicle lateral behaviour and is able to warn the driver for possible tilting of the vehicle. The system is developed for the Dutch transport company of liquified petroleum gas, BK-GAS B.V.

**Pressure**
The total vehicle weight is measured by pressure sensors, connected to the air suspension system of the tractor. The pressure in the air suspension is an indication for the actual vehicle load. By combining the left and right pressure the influence of a tilted road is taken into account when measuring the total actual weight. Also the sensor calibration can be performed on a tilted road, having no result on the determined weight.
During the trip, the signal from the pressure sensors is filtered by a low-pass software filter so that road unevenness does not disturb the measured weight and that loading or unloading cargo is detected.

**Lateral acceleration**
The accelerometer, mounted on the chassis of the tractor, is constantly monitoring the vehicle lateral acceleration. The mounting position on the tractor, like the pressure sensors, ensures an installation on only one articulation of the vehicle. When another semi trailer of the same kind is coupled to the tractor, the system does not have to be installed a second time. Furthermore, the system functions fully autonomously and does not require actions from the driver.

**Tacho**
The system also takes also information from the vehicles tacho to obtain information about actual speed and trip distance.

**Black box**
The black box consists of a Central Processing Unit (CPU) and an EPROM (Electronically Programmable Read Only Memory), containing the lateral acceleration limit at close to tilting of the vehicle (see Section 4). Four times a second the measured lateral acceleration is compared to the acceleration limit, for the specific weight condition, as measured by the pressure sensors. If the measured level of acceleration exceeds the limit value, coming from a model of the vehicle, a warning signal could be given to the driver, providing him with the opportunity to respond adequately.
The system logs the highest acceleration level, together with the weight, velocity and trip distance of every one second and stores it in the systems memory. These values are shown in a histogram, representing 10 categories of lateral acceleration. Furthermore, the ten largest registered accelerations are shown with their appropriate values of vehicle weight and speed.

Normally the system works on the vehicle source, but in case the contact is shut off, there is a battery backup to feed the memory.
The black box has a RS232 output to connect a PC to the system. The PC can be used as an on-line monitoring device during the trip, or can analyze trip data after it is send to PC. This makes the system a monitoring device and therefore an educational tool.

## 3. THE MATHEMATICAL MODEL

### 3.1 In general

As mentioned before, the limit value of the lateral acceleration of a specific vehicle is calculated by a mathematical model of the vehicle. For every possible weight of the vehicle, from empty to fully laden, the maximum lateral acceleration is calculated.
The chosen limit represents the moment when the truck-trailer combination lifts one wheel from the road (so when the vertical force of one of the wheels becomes zero). For a specific vehicle (the system can be used for truck and tractor-semi trailer combinations) a number of parameters are needed to identify the acceleration limit. When the EPROM is programmed, it can be plugged into the black box.

Since the system was developed for BK-GAS, the vehicle to model was a tractor-semi trailer with tank to transport liquified petroleum gas. To show system results, the acceleration is determined for the tank trailer combination.

### 3.2 The tractor - semi trailer model

The dynamic behaviour of a tractor-semi trailer combination, carrying a liquid load, can be seen as a worst case scenario. The difference between a full and empty vehicle is large, resulting in a completely changed dynamic behaviour. The load has its own dynamic properties, influencing the dynamic behaviour of the vehicle and resulting in a possibly increased lateral acceleration level and therefore increased tilt danger compared to a vehicle with the same weight but fixed load. The vehicle to be modelled is a 3-axle tractor with one driven axle and a three axle super single tank semi trailer.

The parameters of the vehicle are shown in Table 1.
Modelling of the vehicle is done in the multi body code BAMMS (Bondgraph based Algorithms for Modelling Multi body Systems). The code offers the user with a toolkit to choose, define or develop subsystems of the vehicle, from very elementary joints to complete axles. The code creates a stand alone programme, with which the vehicle behaviour can be simulated.
The tractor model consists of a 2 axle vehicle, where the rear axle represents both rear axles of the real tractor. Cab suspension is not taken into account.
The semi trailer is modelled as a one axle vehicle, where the only axle represents the three super single axles.
Of all vehicles the roll stiffness is modelled as a torsional stiffness and damping between sprung an unsprung mass. Linear tyre behaviour is expected. The king pin between tractor and trailer is represented as a ball joint with

Table 1 Vehicle model parameters

| | |
|---|---|
| **Tractor** | |
| Tractor mass (incl. axles) | 9000 kg |
| Centre of gravity | 0.92 m |
| Wheel base | 3.5 m |
| Track front | 2.04 m |
| Track rear | 1.83 m |
| Roll stiffness (axle 1) | 620.000 Nm/rad |
| Roll stiffness (axle 2&3) | 1.000.000 Nm/rad |
| **Trailer** | |
| Trailer mass(incl. axles) | 16000 kg |
| Centre of gravity trailer | 2.25 m |
| Mass liquid | 25000 kg |
| Centre of gravity liquid | variable |
| Wheel base | 7.00 m |
| Track | 2.04 m |
| Roll stiffness (axle 1,2&3) | 2.200.000 Nm/rad |

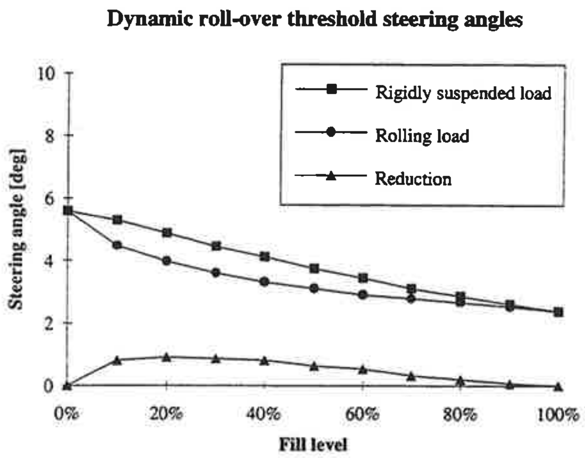


Figure 3 Limit acceleration value of tank vehicle with dynamic and fixed load influence.

restricted angle rotations around lateral and longitudinal axes. The liquid is modelled as a point mass connected to the tank with linear springs in longitudinal, lateral and vertical direction. The total liquid mass is modelled in one centre of gravity.

### 3.3 Simulations

To calculate the limit acceleration values at different levels of vehicle weight, the steady state curve behaviour is simulated. Because the accelerometer is mounted on the chassis of the tractor, therefore not in the centre of gravity of the complete vehicle, the model has to compensate for the positional shift in longitudinal direction.
A number of simulation runs carried out to establish the tilt acceleration at a fixed vehicle weight. This is done for a number of weights of the vehicle (from 0% to 100% load). For the tank vehicle the limit acceleration level as a function of vehicle weight is displayed in Figure 3, together with the effect of a fixed load.

## 4 EVALUATION OF THE SYSTEM

### 4.1 Data gathering

The system was tested by BK-GAS B.V. in 1993/1994, defining a route on which normal gas deliveries took place. More than 70 drivers drove with the system. Two drivers were asked to drive a larger number of trips. Totally over 1000 km was driven with the system. During these trips 4 times the system gave a warning to the driver, but vehicles never tilted.
The trip data was collected from memory by transferring it to PC. Together with the driver the data was analyzed, identifying high lateral accelerations.
Analysis here was performed on a PC with on a spread sheet programme.

### 4.2 Data analysis

At TNO, data analysis was carried out with N-SOFT. Time plots were made of lateral acceleration and vehicle weight, exceeding a threshold of 1 $m/s^2$. Also 3-D histogram plots were made of lateral acceleration against vehicle weight and lateral acceleration against velocity. All these plots were made for every trip, for all trips of the two drivers and for all trips as a total.

Figures 4 and 5 are typical trip time plots of lateral acceleration and velocity. Figures 6 gives the accompanying total trip data in histograms. Decrease of weight at a gas delivery is very well recognisable. The variation around one specific vehicle weight is caused by road irregularities and motion of the liquid. After the first few test trips, the software filter of the pressure sensor data was adjusted to decrease the influence of these disturbances.

In Figure 7 the total number of samples, collected during all tests, are presented in one graph. This graph supports earlier research [2], which indicated that drivers tend to overestimate the capabilities of their vehicle during low speed cornering manoeuvres. The highest lateral accelerations occur around 20 km/h.

Figures 8 and 9 give an impression of differences in driving behaviour of two drivers The diffusion of lateral acceleration against speed is evident. Especially at low speeds the difference between driver one and two become obvious.

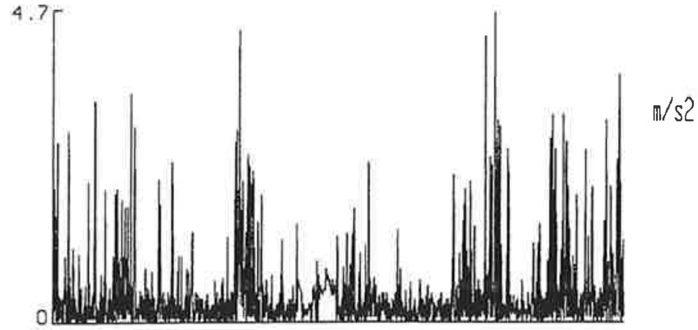


Figure 4 Time plot $a_y$

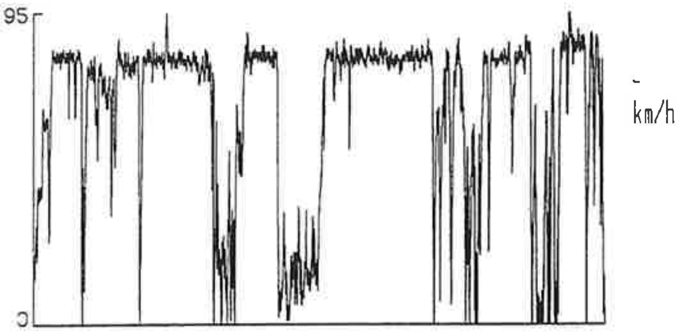


Figure 5 Time plot velocity

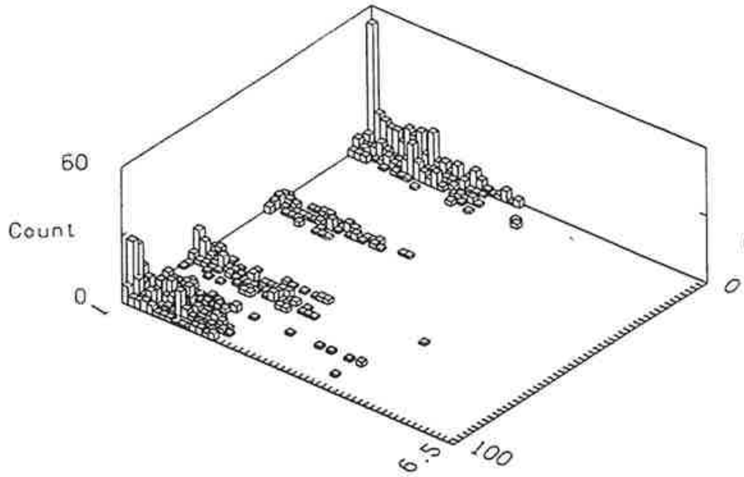


Figure 6 $a_y$ - weight

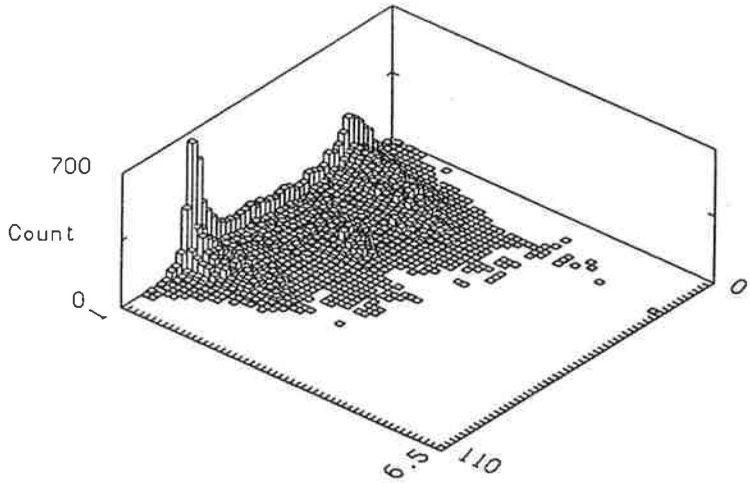


Figure 7 Total of gathered data

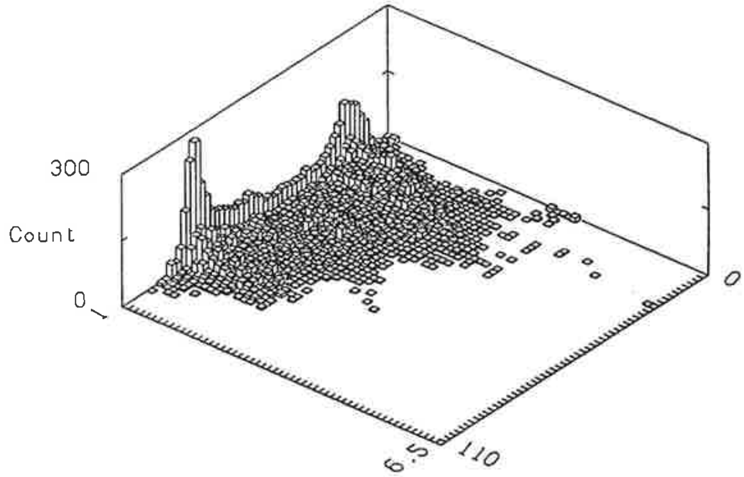


Figure 8 Driver 1

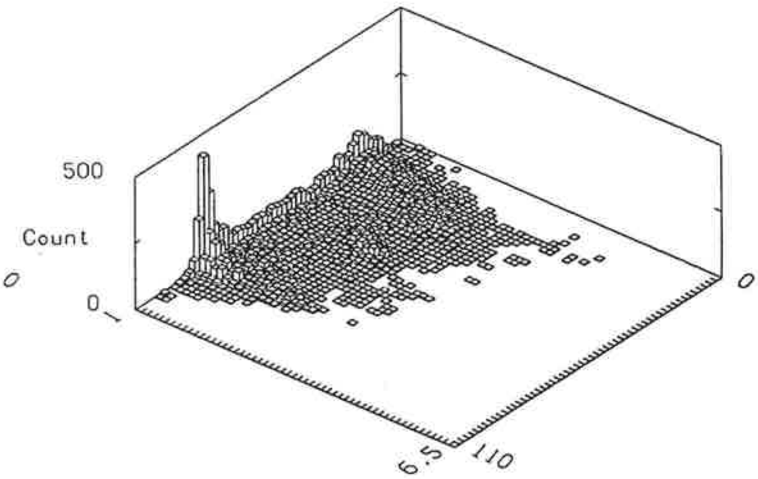


Figure 9 Driver 2

## 5 CONCLUSIONS

- to obtain better insight in the number, cause and effects (social, economical) of tilt accidents, registration of these accidents should be improved, from police reports (for accident reconstruction) to categorization of accidents in a database.
- the data analysis confirms conclusions from earlier research that tilting most likely occurs at speeds around 25 km/h, where the driver tends to overestimate the capabilities of his vehicle;
- the Tilt Warning System in general can be a efficient and cost-effective tool to educate drivers about vehicle capabilities, therefore reducing the number of situations which could result in tilting of the vehicle;
- differences in driver behaviour can be identified by the system, creating the opportunity to provide the driver with individual feedback;
- after initial reserved feeling towards the system, most drivers accepted it after test drives as a useful tool to improve personal safety;
- the Tilt Warning System indicates a potential usage as a driver warning and support system. The influence on driver behaviour and time lag between warning and tilting should be further investigated;
- extension to other registration functions for commercial vehicles is possible (on-board computers, freight monitoring, other telematics applications).

## 6. REFERENCES

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