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# PARAMETER SENSITIVITY OF THE DYNAMIC ROLLOVER THRESHOLD

Erik Dahlberg Scania CV AB, SE - 151 87 Södertälje, Sweden

## *ABSTRACT*

*Knowledge of commercial vehicle rollover mechanics, required in the development of active dynamic control systems and when designing for increased safety, commonly relies on static analysis providing the steady state rollover threshold, SSRT. In a rolling vehicle kinetic energy is always present and that deteriorates the analysis of roll stability from SSRT. Therefore, knowledge of the dynamic rollover threshold, DRT, is equally relevant.*

*In order to investigate the parameter sensitivity of the dynamic rollover threshold, the Taguchi method is applied: simulations are performed according to a specific plan forming an orthogonal matrix existing of high, medium and low parameter values. The influences from five test parameters on SSRT as well as DRT of a truck and a tractor semitrailer combination are calculated, including the corresponding parameter interaction effects. Investigated parameters are frame roll stiffness plus axle roll stiffnesses and roll center heights of front and rear axles.*

*Results show that the different vehicles are unequally sensitive to parameter changes: the rear axle roll characteristics are the most important semitrailer parameters, while the front axle roll stiffness is most important for the truck. An important result yielding from this is that two vehicles can be equally stable statically but different dynamically.*

## INTRODUCTION

Commercial vehicle rollover has grave implications: the accident type contributes substantially to injuries but also to environmental damage. Several vehicle occupants are seriously injured or killed every year and vehicles carrying hazardous goods often waste it. When a driver detects the vehicle approaching or exceeding the stability limit, the possibility of returning to a stable driving situation is very small or does not exist. Several of these accidents are hardly avoidable today, e.g. the extremes in the driver-vehicle-environment system: the driver falling asleep at the wheel, the roadway collapsing during cornering or the vehicle having such a low level of roll stability that a simple steering input results in rollover. However, it is possible to identify situations, where the rollover can be avoided by using stability system assistance to the driver and/or the vehicle.

### Avoiding the Accident

In 1990, Preston-Thomas and Woodrooffe created a rollover warning device feasibility study [1][1], showing that 42% of more than 2000 investigated incidents could be avoided with a system installed, warning of the incipient risk. They propose a passive warning device, similar to other passive devices and learning systems presented by e.g. Ervin et al. [2] and Nelligan and Zein [3].

Active stability systems, e.g. Vehicle Dynamics Control, VDC discussed by Hecker et al. [4], avoid rollovers more efficiently than passive systems. The vehicle detects the prevailing conditions and stability margins and supports the driver at an early stage by returning the combination to a stable condition. This is achieved by applying a suitable braking force at each wheel, whereby speed is reduced while a stabilising yaw torque is generated, assisting the driver in managing the situation. Several similar active systems are suggested, e.g. the rearward amplification suppression, RAMS [2] and the pure roll stability system, ARB presented by Wielenga [5]. Active as well as passive systems require *detection of instability* and this implies a need for increased knowledge of rollover mechanics.

## THE DYNAMIC ROLLOVER THRESHOLD

The on-road rollover, in contrast to the off-road event, is the most thoroughly documented type, being the easiest to analyse and control: yaw and/or roll stability systems possibly avoid these rollovers. Its most common analysis

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[1] Numbers in brackets indicate end paper references

approach is the static, from which the rollover threshold is calculated. During steady state cornering on an even road under no influence of external forces, the level of lateral acceleration determines whether the vehicle rolls over or not. The following definition is applicable:

Definition 1: The Steady State Rollover Threshold, SSRT is the maximum value of lateral acceleration, which the vehicle when driving in steady state may resist in order not to rollover.

Numerous models exist for the calculation of SSRT: generally two-dimensional roll plane models, the static stability factor, SSF being the simplest. It is defined as one half of the average front and rear track-width, divided by the total CG height. Through the simplifying assumption that a vehicle behaves as a rigid body, SSF equals SSRT as a first order approximation. SSF is the least conservative estimation among applied quasi-static models, reported by e.g. Chrstos and Guenther [6]: when comparing it to any established model considering flexibility, it predicts a higher threshold.

During cornering, the vehicle rolls due to suspension compliance resulting in lateral CG shift toward the outside of the turn. This offset reduces the lever arm on which the gravity force acts to resist rollover. In order to refine the model, this effect is considered by introducing suspension roll center and stiffnesses. Consequently, models with higher precision exist including other flexibilities, such as tire and chassis frame, cf. e.g. [1], Lozia [7] and Ruhl and Ruhl [8].

However, in the real world, rollover does not take off during steady state driving, it occurs during a transient manoeuvre, at acceleration levels lower than SSRT, Rakheja and Piché [9]. Hence there exists a lateral acceleration interval within which rollover can, but does not necessarily occur. Since SSRT is the best case measure of roll stability, the worst case measure is also needed in order to encircle the range where instability is possible. The following definition is applicable when driving on a smooth surface under no influence of external forces:

Definition 2: The Dynamic Rollover Threshold, DRT is the minimum absolute peak value of lateral acceleration of all manoeuvres bringing the vehicle to rollover.

This definition implies that DRT is a worst case measure of roll stability: conditions are necessary but not sufficient for rollover. Other proposals for a dynamic measure of roll instability exist, like the step acceleration threshold by Bernard et al. [10], which is limited to one vehicle model only. Variants of the dynamic acceleration threshold are also presented by e.g. Marine et al. [11] and by Das et al. [12].

## A METHOD DETERMINING DRT

The calculation method presented by the author in [13], determines DRT in accordance with the definition above. It is here only briefly represented.

### The Roll Energy Diagram

The roll energy diagram includes energy considerations: in rough outline it consists of the potential energy required to bring the vehicle into roll instability and the kinetic energy present in the system, both as a function of lateral acceleration. The diagram, first presented in [14], is successfully developed in [13].

When the vehicle is stable, driving straight ahead, the potential energy is defined as zero. By applying a lateral acceleration and finding the static equilibrium, that acceleration's *equilibrium potential energy* originating in spring deflections and the translation of CG against the gravitational and lateral acceleration potential fields results.

The diagram presents two curves of equilibrium potential energy as functions of steady state lateral acceleration, stable and unstable driving. The lower curve starts at stable driving straight ahead (at the origin) and continues for increasing steady state lateral acceleration up to stable driving at SSRT (rightmost point of the curve). The upper curve on the other hand is more spectacular in its interpretation: it starts at straight ahead driving on the wheels of one side only(!) and continues for that kind of driving at increasing lateral acceleration up to SSRT.

*The rollover energy*, the minimum required bringing the vehicle to rollover, is simply the energy difference between the boundaries, the difference between the two equilibrium states. The rollover energy decreases as acceleration increases, approaching zero at SSRT.

The lower curve is interpreted as the negative *unrestrained kinetic energy*: introducing a step acceleration laterally releases the corresponding energy. Therefore, DRT occurs at the intersection between the upper curve and the abscissa: the lateral acceleration at which the unrestrained kinetic equals the rollover energy. At this acceleration, the released kinetic energy equals the minimum required causing rollover, fulfilling the criteria of the dynamic rollover threshold definition.

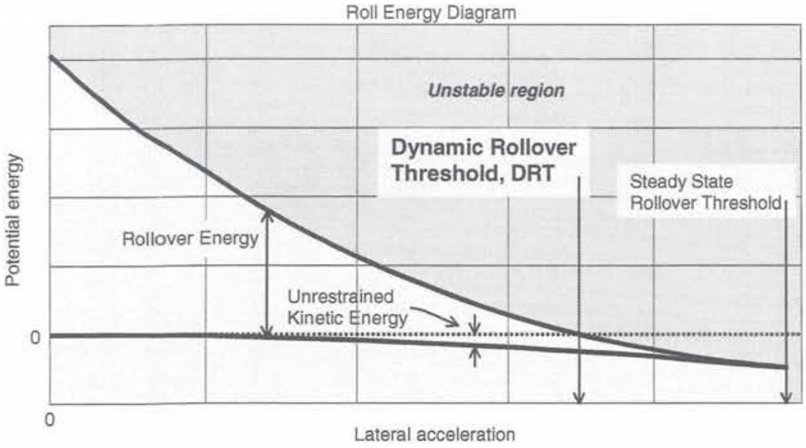

Figure 1 - The Roll Energy Diagram determining DRT

By deriving the roll energy diagram, using a suitable calculation program and a valid model, steady state and dynamic rollover thresholds are identified.

[13] shows that roll damping is considered in a modified DRT, but one lateral acceleration value can not fully describe the dynamic forces acting on the rolling vehicle. The measure is also incapable of describing yaw induced rollover, e.g. instability originating in rearward amplification. It is however a very manageable measure: DRT using the presented method consists of one engineering value only and it is as close to the definition as is possible.

## MODEL EXAMPLES

One important quality of DRT is its *model independence*, i.e. it is applicable to any vehicle rollover model. Here, the method is applied to two vehicle models: describing a single truck and a semitrailer combination.

### The Single Truck

The single truck model includes five rigid bodies and five roll degrees of freedom (5DOF): front and rear axles, cab and the front and rear parts of the chassis, interconnected by rotational spring-damper elements, giving each body 1DOF. The frame flexibility is also included, but in order to avoid a complex FE-model, two chassis bodies are simply connected with a rotational stiffness. Tires are assumed stiff in the lateral direction to limit the DOF, but they are compliant vertically.

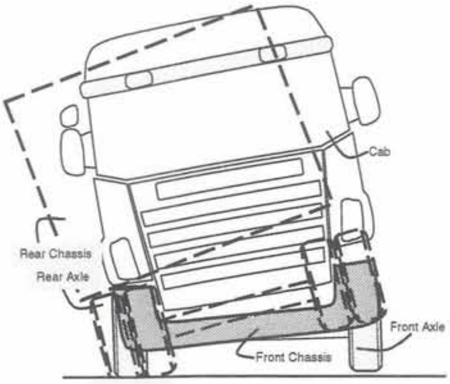

Figure 2 - Front view of truck model

### The Semitrailer

The semitrailer pulled by a tractor is the most common combination rolling over, wherefore this investigation also includes such a model, originating in the truck described above. Three bodies are added, representing the semitrailer (one wheel axle and two chassis bodies), while the cab body is excluded. The fifth wheel is a rotational stiffness in the 7DOF model.

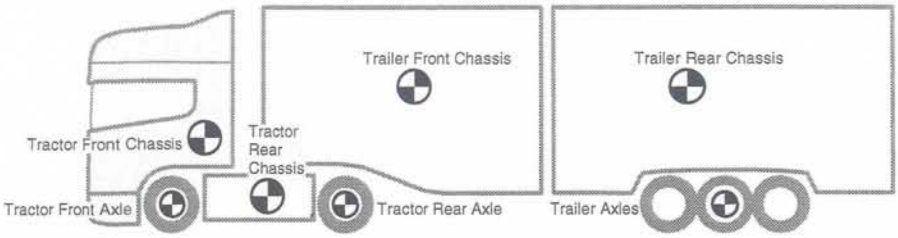

Figure 3 - Side view of semitrailer model

## THE TAGUCHI METHOD

The Taguchi method, one of several multivariate analytical methods, is frequently used in quality engineering, but also applicable in product development. A test plan, described by an orthogonal matrix, is used enabling testing of more than one parameter at a time, without repetition, at two or more levels. Using two levels yields a linear and three or more a non-linear estimation of the parameter sensitivity. The method is thoroughly described by e.g. Phadke [15] and Gore and Davis [16].

One of two advantages with the Taguchi method over the traditional one-at-a-time method can be chosen: the number of tests can be reduced considerably (reduced multi-variate testing) or the effects of parameter interaction can be derived. The latter is chosen in this investigation.

## PARAMETERS

In this investigation, the Taguchi method is used to analyse the influence of five truck parameters on the static and dynamic rollover thresholds of the vehicles described above. The method determining DRT described above is applied on computer calculations in the multi-body dynamics software ADAMS and simultaneously, SSRT is calculated. Since the parameter sensitivity of SSRT is more thoroughly documented in the literature, this investigation focuses on DRT.

The models are chosen in order to clarify any possible difference in parameter sensitivity to DRT, and its divergence from SSRT, between the rigid truck and the semitrailer combination. The parameter values defining the roll stability properties of the vehicles are therefore chosen as being equal where applicable, so the vehicles have equal total CG height and except for the load on the truck, it is equal to the tractor in the semitrailer combination.

There are a number of parameters that are likely to influence DRT and SSRT, but in order to limit this investigation only five parameters are chosen. Since it is desirable to investigate the improvement in roll stability that is possible through a realistic redesign of the vehicle, CG height and track-width are left out even though they probably influence the rollover thresholds considerably. Instead five parameters that are more easily changed on a real vehicle, all set by the vehicle manufacturer, are chosen: the roll stiffness of the frame and the roll stiffnesses and roll center heights of both the front and the rear axles, cf. table 1. These parameters are known to influence SSRT, cf. e.g. Winkler et al. [17].

Table 1 - Alternated parameters and their levels

| **Parameters** | **Low level** | **Intermediate level** | **High level** |
|---|---|---|---|
| **A** Frame Roll Stiffness | 200 kNm/rad | 400 kNm/rad | 600 kNm/rad |
| **B** Roll Center Height Front | 0.20 m | 0.40 m | 0.60 m |
| **C** Roll Stiffness Front | 200 kNm/rad | 400 kNm/rad | 600 kNm/rad |
| **D** Roll Stiffness Rear | 500 kNm/rad | 1000 kNm/rad | 1500 kNm/rad |
| **E** Roll Center Height Rear | 0.30 m | 0.60 m | 0.90 m |

To investigate non-linearities among the influences, each parameter is alternated on three realistically chosen levels, cf. table 1. It is important to keep in mind that the results of this investigation depend on the range within which the parameters vary. All other parameters are listed in Appendix A.

## EXPERIMENTS

Several standard orthogonal arrays, designed for multivariate analysis are found in the literature, cf. e.g. [15], and for this investigation an $L_{27}$ is chosen. This is a $3^{13}$-array, indicating that it has 13 columns at three levels, enabling testing of up to 13 parameters at three levels each. However in this investigation, since only five parameters are used, several interaction effects are also studied: all interactions between the frame roll stiffness and the other factors are chosen.

In table B.1 (cf. appendix B), the $L_{27}$ array is presented with grey columns showing the varied parameters and their levels. The non-shaded columns do not set any parameter value levels, they are neglected since interactions are studied. The orthogonal array has 27 rows, indicating that 27 experiments are conducted in this test. Since SSRT and DRT are simultaneously yielded once the roll energy diagram is derived, 27 truck simulations are required and an equal number for the semitrailer.

Tables B.1 and 1 are combined into the left part of table C.1 in appendix C defining parameter settings during the 2·27 simulations. In that table, the base for the following experiments, empty columns are left out since they are not used during experiments. Simulations are conducted as specified by the rows of table C.1 and for each computer calculation, the resulting SSRT and DRT are logged.

## RESULTS

The grey shaded fields in table C1 include the results from the experiments. Some of the resulting thresholds are very low since the models simulate high CG vehicles and since some parameter combinations become very unfavourable: DRT varies between 1.38 $m/s^2$ and 2.98 $m/s^2$ while SSRT varies between 1.87 $m/s^2$ and 3.51 $m/s^2$.

The simulation results are processed and the resulting effect of a parameter level is defined as the deviation caused by the average of the results at that parameter level from the overall mean. Every parameter has thereby three deviation values or main effects: when keeping it low, intermediate and high as shown in the line diagrams, e.g. figure 7. These main effects are linearised by subtracting the effect of keeping a parameter at its low value from the effect of keeping it high, as in the bar diagrams, e.g. figure 4. Hence, the effect of a parameter is the deviation a unit-change in that parameter causes to the result, e.g. the effect of the frame roll stiffness on SSRT equals the change in SSRT when the stiffness is increased from its low 200 to its high 600 kNm/rad.

Furthermore, the resulting SSRT and DRT, when changing more than one parameter, depend not only on the main effects but also on the interaction effects of two or more parameters. These interactions are not as easily calculated as the main effects: the linearised interaction effects of two parameters are calculated, with the intermediate level excluded, by subtracting the average result with the parameters kept at different levels from the average result keeping them at equal. So, the combination effect of two parameters is *the additional* deviation a simultaneous unit-change in both parameters causes to the result compared to sum of the parameter effects only.

Interactions are analysed in diagrams where the deviation from the overall mean when combining one level of a parameter with one level of another is calculated. To derive the combination of two parameters at three levels, nine such calculations are required. Non-linear interactions are recognised by the non-parallelism in these diagrams.

### Truck Results

The linearised effects of the truck simulations are given in figures 4 to 6. A Pareto diagram disregards the signs, but presents the sizes of the effects arranged in a descending scale.

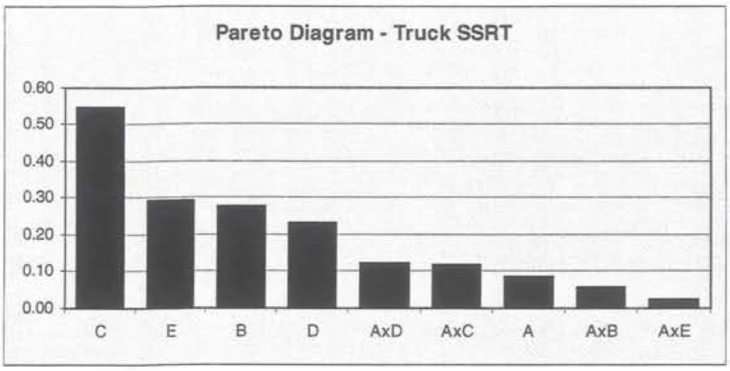

Figure 4 - Linearised main and interaction effects of the truck SSRT

As can be seen in figures 4 and 5, the front axle roll stiffness is by far the most important parameter for both rollover thresholds of this truck. Roll stiffness and roll center height of the rear axle are also important parameters for DRT, while these two plus the roll center height of the front are important for SSRT. DRT appears to be influenced more than SSRT by the frame stiffness, which in interaction with the front roll stiffness also has a slight effect on the dynamic threshold. The other combination effects studied are negligible.

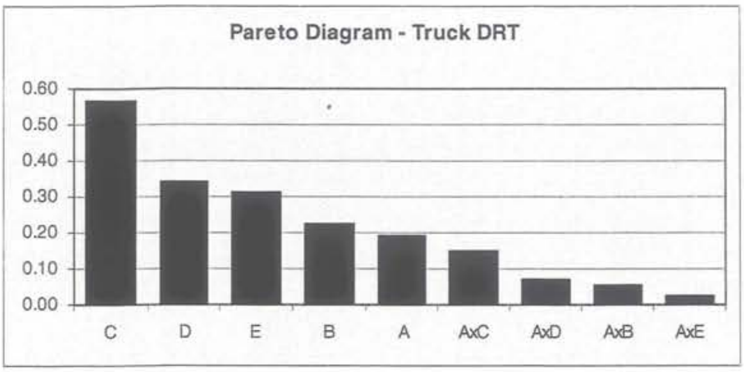

Figure 5 - Linearised main and interaction effects of the truck DRT

Figure 6 shows the linearised parameter effects for DRT divided by SSRT, which indicates how much the parameter change influences relative stability, i.e. the size of the interval within which rollover can occur. By changing a parameter that highly influences that quotient, the stability of the vehicle is more affected than expected if DRT is not considered. The stiffnesses, rear axle the most, clearly affect the relative stability of this truck, while all other effects, except for that from the rear axle roll center height, are negligible.

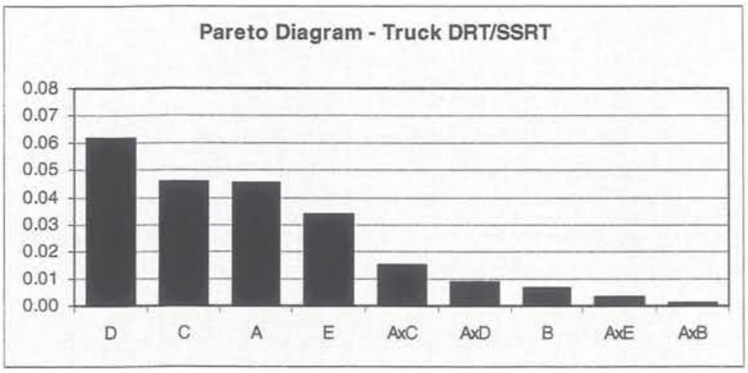

Figure 6 - Linearised main and interaction effects of the truck DRT/SSRT

Figure 7 presents all main effects on the truck DRT, showing that all are positive and slightly non-linear: the effect is higher when changing from the low level to the intermediate than from the intermediate to the high.
Figure 8, showing the non-linear interactions of the truck DRT, reveal that the higher the frame stiffness, the more important is the front axle roll stiffness (AxC) but all other interactions are small.

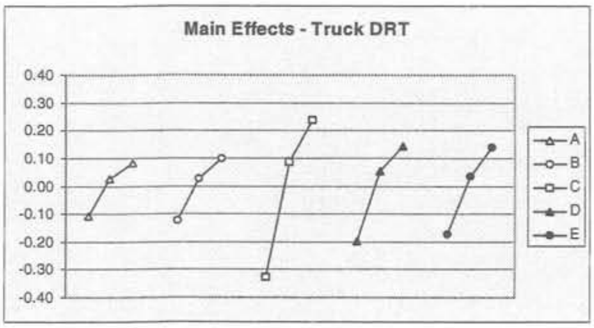

Figure 7 - Main effects of the truck DRT simulations

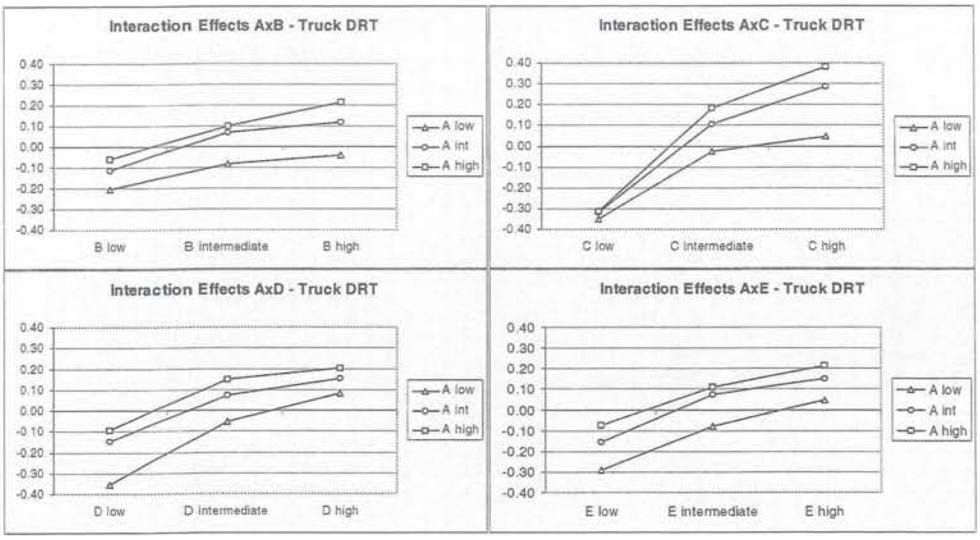

Figure 8 - Interaction effects of the truck DRT simulations

## Semitrailer Results

Semitrailer results are shown in figure 9 to 13.

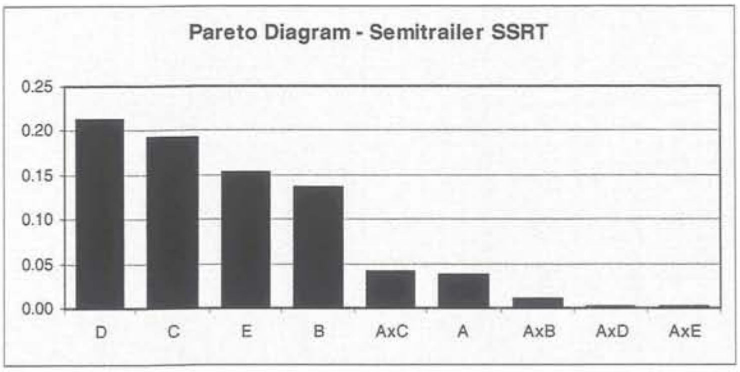

Figure 9 - Linearised main and interaction effects of the semitrailer SSRT

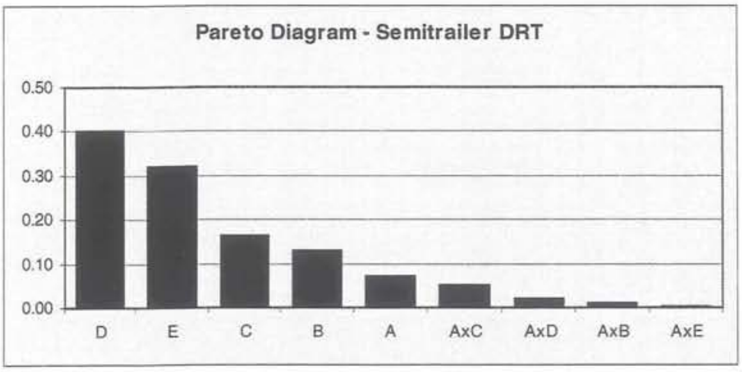

Figure 10 - Linearised main and interaction effects of semitrailer DRT

As shown in figures 9 and 10, DRT effects from the rear axle characteristics are very important for the semitrailer. The rear axle roll stiffness is the most important parameter for both thresholds and for DRT, the rear axle roll center height is also important. The effects of front and rear axle roll stiffnesses and roll center heights are of equal magnitude for SSRT, but for DRT, front axle roll characteristics have only a small influence. Other studied DRT as well as SSRT effects are negligible. It is important to point out that the scales differ between DRT and SSRT results and between truck and semitrailer results.

Figure 11 indicates that only the rear axle roll characteristics have a significant influence on the relative stability of the semitrailer combination. Both relevant effects are positive, i.e. the parameters affect DRT more than SSRT.

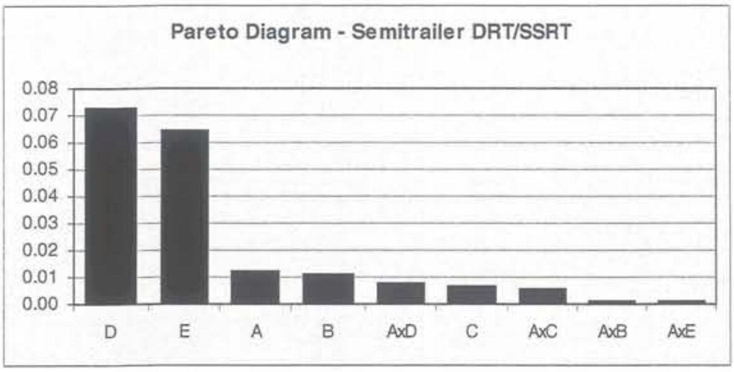

Figure 11 - Linearised main and interaction effects of the semitrailer DRT/SSRT

Figure 12, presenting all main effects on the semitrailer DRT, shows that all are positive and all but the front axle roll stiffness are slightly non-linear with higher gain in the lower range. The front roll stiffness is more non-linear: the highest DRT is reached when that parameter is kept at its intermediate level.

Figure 13, finally shows all non-linear interactions in the semitrailer DRT simulations being small but AxC: the higher the frame stiffness, the less pronounced is the non-linear effect of the front axle roll stiffness. Results in figure 13 are differently scaled than the corresponding truck results in figure 8.

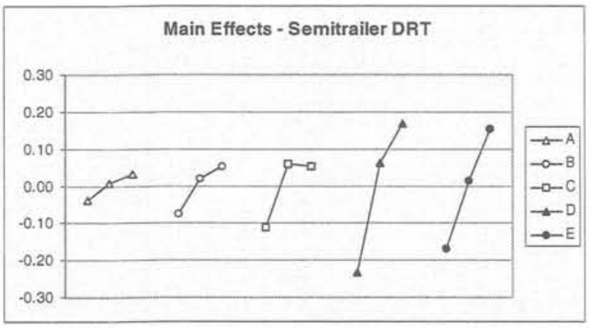

Figure 12 - Main effects of the semitrailer DRT simulations

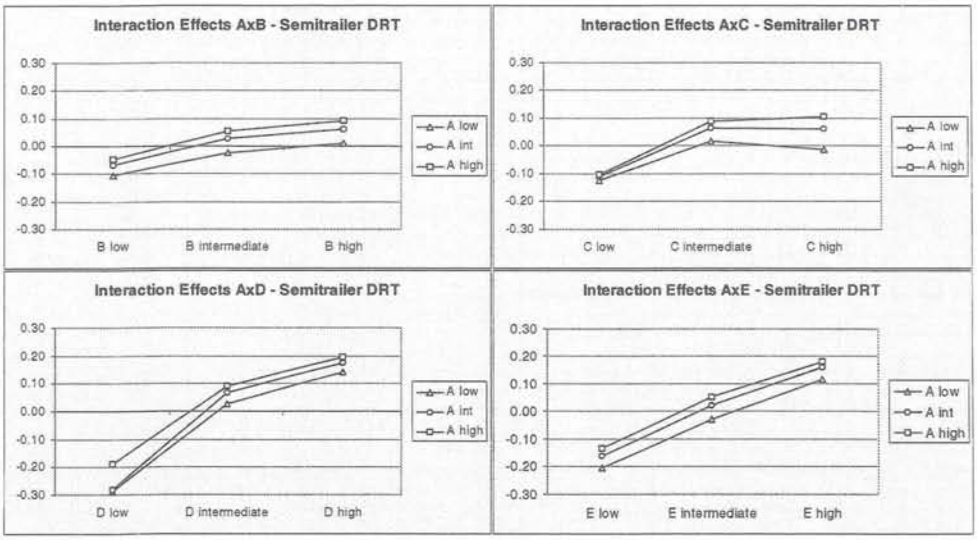

Figure 13 - Interaction effects of the semitrailer DRT simulations

## CONCLUSIONS

In this work, a method deriving the dynamic rollover threshold, a complement to the static threshold is analysed. Results from applying the Taguchi method to simulations of the static and dynamic rollover thresholds of a rigid truck and a semitrailer combination, in which five parameters and their interactions are studied, show that the parameters influence the different vehicles unequally:

- Among the studied parameters, the rear axle roll stiffness and roll center height are important to the sensitivity of the vehicles. While they are the most important semitrailer parameters, the front axle roll stiffness is the most important on the truck.
- The frame stiffness is less important: a tendency that is most pronounced in the semitrailer results. However, the interaction effect of the front axle and the frame stiffnesses are noticeable in DRT. In order to gain dynamic stability by increasing the front axle roll stiffness it is important to keep the torsional stiffness of the frame high. The other combination effects are negligible.
- The parameter effect magnitudes on the truck are larger overall than on the semitrailer, since the trailer axle additionally resists the roll overturning moment.

The most important conclusion is that, since DRT and SSRT are not equally affected by parameters, vehicles can be *equally stable statically but different dynamically*. Therefore, if the static but not the dynamic rollover threshold is analysed, a vehicle redesign can reduce the roll stability even though it appears to preserve or even improve it.

## ACKNOWLEDGEMENTS

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## DEFINITIONS AND ABBREVIATIONS

| | |
|---|---|
| A | Test Parameter: Frame Torsional Stiffness [Nm/rad] |
| B | Test Parameter: Front Axle Roll Center Height [m] |
| C | Test Parameter: Front Axle Roll Stiffness [Nm/rad] |
| D | Test Parameter: Rear Axle Roll Stiffness [Nm/rad] |
| E | Test Parameter: Rear Axle Roll Center Height [m] |
| $L_{27}$ | Orthogonal Test Array with 27 Rows |
| ADAMS | Automatic Dynamic Analysis of Mechanical Systems |
| ARB | Anti Rollover Braking |
| CG | Center of Gravity |
| DOF | Degrees of Freedom |
| DRT | Dynamic Rollover Threshold |
| RAMS | Rearward Amplification Suppression |
| SSF | Static Stability Factor |
| SSRT | Steady State Rollover Threshold |
| VDC | Vehicle Dynamics Control |

## APPENDIX A

The values used in the simulations are listed in tables A.1 and A.2. All values are realistic but do not necessarily correspond to any existing vehicle.

Table A.1 - Single truck parameters

| | | |
|---|---|---|
| **CG heights** | Front axle | 0.50 m |
| | Rear axle | 0.50 m |
| | Front chassis | 1.80 m |
| | Rear chassis | 2.30 m |
| | Cab | 2.00 m |
| **Masses** | Front axle | 700 kg |
| | Rear axle | 1300 kg |
| | Front chassis | 3000 kg |
| | Rear chassis | 12000 kg |
| | Cab | 1000 kg |
| (Inter-body) **Roll center heights** | Chassis front to rear | 0.90 m |
| | Chassis front to cab | 1.40 m |
| **Roll stiffnesses** | Chassis front to cab | 500 kNm/rad |
| **Vertical tire stiffnesses (one side)** | Front axle tires | 950 kN/m |
| | Rear axle tires | 1900 kN/m |
| **Geometry** | Wheel base | 3.70 m |
| | Distance front axle to CG | 2.06 m |
| | Front axle track-width | 2.06 m |
| | Rear axle effective track-width | 1.86 m |

Table A.2 - Semitrailer parameters

| | | |
|---|---|---|
| **CG heights** | Trailer front chassis | 2.37 m |
| | Trailer rear chassis | 2.37 m |
| | Trailer axles (merged) | 0.50 m |
| | Tractor front chassis (merged with cab) | 1.20 m |
| | Tractor rear chassis | 1.10 m |
| **Masses** | Trailer front chassis | 15000 kg |
| | Trailer rear chassis | 15000 kg |
| | Trailer axles (merged) | 2000 kg |
| | Tractor front chassis (merged with cab) | 4000 kg |
| | Tractor rear chassis | 2000 kg |

Table A.2 - Semitrailer parameters, continued

| | | |
|---|---|---|
| **(Inter-body) Roll center heights** | Fifth wheel | 1.15 m |
| | Trailer chassis front to rear | 1.00 m |
| | Trailer axle to rear trailer chassis | 0.40 m |
| **Roll stiffnesses** | Fifth wheel | 5000 kNm/rad |
| | Trailer chassis front to rear | 2000 kNm/rad |
| | Trailer axle to rear trailer chassis | 4500 kNm/rad |
| **Vertical tire stiffness (one side)** | Trailer axle tires | 2850 kN/m |
| **Geometry** | Distance tractor front axle to CG | 1.11 m |
| | Distance tractor CG to fifth wheel | 1.70 m |
| | Distance fifth wheel to trailer CG | 4.07 m |
| | Distance trailer CG to trailer axle | 1.85 m |
| | Trailer axle track-width | 2.00 m |

## APPENDIX B

In the following table, the $L_{27}$ array defining the parameter levels during the 27 tests is presented. Grey-shaded columns show the parameter levels while non-shaded columns are neglected in the analysis and are shown only since they are necessary to demonstrate that the chosen array is orthogonal, a requirement in the Taguchi method. Due to this orthogonality, not all possible combinations of the five parameters on the three levels are required.

Table B.1 - The standard $L_{27}$ orthogonal array

| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Exp. no.** | A | B | | | C | | | D | | | E | | |
| **1** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **2** | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| **3** | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| **4** | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 3 |
| **5** | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 1 | 1 |
| **6** | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 1 | 1 | 2 | 2 | 2 |
| **7** | 1 | 3 | 3 | 3 | 1 | 1 | 1 | 3 | 3 | 3 | 2 | 2 | 2 |
| **8** | 1 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 1 | 3 | 3 | 3 |
| **9** | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 1 |
| **10** | 2 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| **11** | 2 | 1 | 2 | 3 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 |
| **12** | 2 | 1 | 2 | 3 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 |
| **13** | 2 | 2 | 3 | 1 | 1 | 2 | 3 | 2 | 3 | 1 | 3 | 1 | 2 |
| **14** | 2 | 2 | 3 | 1 | 2 | 3 | 1 | 3 | 1 | 2 | 1 | 2 | 3 |
| **15** | 2 | 2 | 3 | 1 | 3 | 1 | 2 | 1 | 2 | 3 | 2 | 3 | 1 |
| **16** | 2 | 3 | 1 | 2 | 1 | 2 | 3 | 3 | 1 | 2 | 2 | 3 | 1 |
| **17** | 2 | 3 | 1 | 2 | 2 | 3 | 1 | 1 | 2 | 3 | 3 | 1 | 2 |
| **18** | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 2 | 3 | 1 | 1 | 2 | 3 |
| **19** | 3 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 |
| **20** | 3 | 1 | 3 | 2 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 |
| **21** | 3 | 1 | 3 | 2 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 |
| **22** | 3 | 2 | 1 | 3 | 1 | 3 | 2 | 2 | 1 | 3 | 3 | 2 | 1 |
| **23** | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 3 | 2 | 1 | 1 | 3 | 2 |
| **24** | 3 | 2 | 1 | 3 | 3 | 2 | 1 | 1 | 3 | 2 | 2 | 1 | 3 |
| **25** | 3 | 3 | 2 | 1 | 1 | 3 | 2 | 3 | 2 | 1 | 2 | 1 | 3 |
| **26** | 3 | 3 | 2 | 1 | 2 | 1 | 3 | 1 | 3 | 2 | 3 | 2 | 1 |
| **27** | 3 | 3 | 2 | 1 | 3 | 2 | 1 | 2 | 1 | 3 | 1 | 3 | 2 |

# APPENDIX C

Table C.1 defines the parameter settings during the simulations and presents the results. The non-shaded part of the table is created by combining table B.1 and table 1 presented in the chapter Parameters.

Table C.1 - The 27 experiments, the control factor level combinations and the results

| | **Parameters** | | | | | **Truck** | | **Semitrailer** | |
|---|---|---|---|---|---|---|---|---|---|
| **Exp. no.** | A | B | C | D | E | **SSRT** | **DRT** | **SSRT** | **DRT** |
| | kNm/rad | m | kNm/rad | kNm/rad | m | $m/s^2$ | $m/s^2$ | $m/s^2$ | $m/s^2$ |
| **1** | 200 | 0.20 | 200 | 500 | 0.30 | 1.87 | 1.38 | 2.92 | 2.04 |
| **2** | 200 | 0.20 | 400 | 1000 | 0.60 | 2.70 | 2.22 | 3.44 | 2.67 |
| **3** | 200 | 0.20 | 600 | 1500 | 0.90 | 2.97 | 2.55 | 3.43 | 2.90 |
| **4** | 200 | 0.40 | 200 | 1000 | 0.90 | 2.60 | 2.14 | 3.37 | 2.76 |
| **5** | 200 | 0.40 | 400 | 1500 | 0.30 | 2.74 | 2.26 | 3.39 | 2.69 |
| **6** | 200 | 0.40 | 600 | 500 | 0.60 | 2.66 | 2.11 | 3.23 | 2.41 |
| **7** | 200 | 0.60 | 200 | 1500 | 0.60 | 2.67 | 2.19 | 3.35 | 2.76 |
| **8** | 200 | 0.60 | 400 | 500 | 0.90 | 2.75 | 2.21 | 3.38 | 2.62 |
| **9** | 200 | 0.60 | 600 | 1000 | 0.30 | 2.76 | 2.24 | 3.43 | 2.58 |
| **10** | 400 | 0.20 | 200 | 500 | 0.30 | 1.90 | 1.44 | 2.92 | 2.06 |
| **11** | 400 | 0.20 | 400 | 1000 | 0.60 | 2.71 | 2.32 | 3.45 | 2.71 |
| **12** | 400 | 0.20 | 600 | 1500 | 0.90 | 2.96 | 2.66 | 3.47 | 2.95 |
| **13** | 400 | 0.40 | 200 | 1000 | 0.90 | 2.55 | 2.15 | 3.36 | 2.77 |
| **14** | 400 | 0.40 | 400 | 1500 | 0.30 | 2.74 | 2.35 | 3.42 | 2.73 |
| **15** | 400 | 0.40 | 600 | 500 | 0.60 | 2.93 | 2.46 | 3.28 | 2.51 |
| **16** | 400 | 0.60 | 200 | 1500 | 0.60 | 2.63 | 2.21 | 3.36 | 2.77 |
| **17** | 400 | 0.60 | 400 | 500 | 0.90 | 2.89 | 2.41 | 3.42 | 2.69 |
| **18** | 400 | 0.60 | 600 | 1000 | 0.30 | 2.91 | 2.50 | 3.48 | 2.65 |
| **19** | 600 | 0.20 | 200 | 500 | 0.30 | 1.91 | 1.46 | 2.91 | 2.07 |
| **20** | 600 | 0.20 | 400 | 1000 | 0.60 | 2.71 | 2.38 | 3.46 | 2.73 |
| **21** | 600 | 0.20 | 600 | 1500 | 0.90 | 2.96 | 2.74 | 3.50 | 2.98 |
| **22** | 600 | 0.40 | 200 | 1000 | 0.90 | 2.53 | 2.15 | 3.36 | 2.77 |
| **23** | 600 | 0.40 | 400 | 1500 | 0.30 | 2.74 | 2.41 | 3.44 | 2.75 |
| **24** | 600 | 0.40 | 600 | 500 | 0.60 | 3.07 | 2.50 | 3.31 | 2.57 |
| **25** | 600 | 0.60 | 200 | 1500 | 0.60 | 2.61 | 2.21 | 3.36 | 2.78 |
| **26** | 600 | 0.60 | 400 | 500 | 0.90 | 2.96 | 2.52 | 3.43 | 2.72 |
| **27** | 600 | 0.60 | 600 | 1000 | 0.30 | 2.99 | 2.67 | 3.51 | 2.70 |