SUBJECTIVE AND OBJECTIVE EVALUATION OF AN OUTRIGGER CONSTRUCTION'S EFFECT ON ROLLOVER

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ABSTRACT

This paper deals with the influence of an outrigger on roll stability of a load dependent LCV (light commercial vehicle), since they are frequently inclined in rollover accidents because of the high CG (centre of gravity), inaccurate loading. That's why, in recent years, ESP (Electronic Stability Program) function has also been integrated in them. Our outrigger based rollover controllers (that contain 1 support and 2 supports per side) were realized, simulated to assess objectively and the influence of the manoeuvres has been tested on the dynamic simulator via questionnaire as a subjective evaluation. Just because not only the controller but also the reactions of the driver will influence the stability.

INTRODUCTION

The simulator MARS in Automotive and Power Train Engineering, Helmut Schmidt University-University of the Federal Armed Forces Hamburg has an 8 DOF (degree of freedom) motion system which is shown in Figure 2. It is operated inside an experimental cab, within a driving environment.

With the control instruments (Steering wheel, Gas and Brake pedals) that are obtained from original parts of a real vehicle, and the driver's view system is provided by three monitors that are inside the cab, besides one that arranges the view outside the cab for the employment of extensive measuring technique (inertial platform, acceleration sensor, bio feedback, camera, etc..) prepared, which has been already used with numerous attempts.

Also there is a static simulator in Automotive and Power Train Engineering, Helmut Schmidt University-University of the Federal Armed Forces Hamburg that is given in Figure 1.

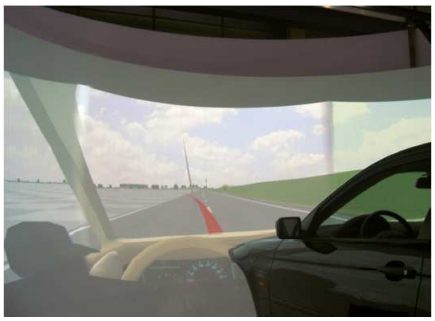

Figure 1. Static Driving Simulator

Figure 2. Dynamic Driving Simulator (Modular Automotive Research Simulator-MARS)

The computation of the vehicle dynamics is prosecuted on both simulators by CarSim. An extension of the model, additional interactive direct access or also responding and configuring of the interfaces are made by the software MATLAB/Simulink.

On test stand, a real time is realized via an additional real time computer (Target) with the operating system QNX and the platform RT-Lab whereas vehicle dynamics computer is called as Host. The interfaces to the control instruments and/or armatures are made by analogue, digital IO modules, which as modules in the real time computer condition that responds motion system by TCP/IP.

The paper deals with the influence of an outrigger on roll stability of a LCV (light commercial vehicle), with different driving manoeuvres and scenarios, while LCVs frequently intend to have accident because of the high CG (centre of gravity) and inaccurate loading [1, 2]. That's why ESP function has also been put in the LCVs in recent years. Exemplary conception of used Simulink models is dealt the comprehensibility and the possibilities of the existing total concept. In addition, a view on possible future applications and/or projects, which with the existing structure within the range HIL (Hardware in Loop)/SIL (Software in Loop)/MIL(Man in Loop) are able to be realized.

In order to evaluate the effect of the outrigger system on the vehicle's safety, our own outrigger based rollover controller was realized. Objective and subjective tests with standard handling manoeuvres showed the influence of outrigger on car stability. Because especially the feeling of the driver are of importance. Just because not only the controller but also the reactions of the driver will influence the handling stability.

Here is also pointed out the influence of the simulator on closed-loop relevant rollover manoeuvre (double lane change). Subjective Assessments have been done on the dynamic simulator.

Modelling of an Outrigger System for Rollover Prevention

In this study, two different types of outrigger have been simulated and compared to each other. One of them is that it contains a supporting a side and the second one is that it has two supportings for a side which has been given in Figure 3 and 4 respectively.

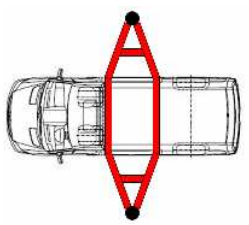

Figure 3. Outrigger with one supporting per a side.

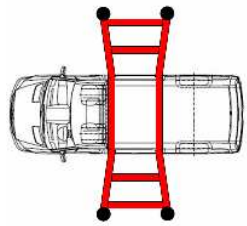

Figure 4. Outrigger with two supportings per a side.

The integration of a supporting device in the driving dynamics program CarSim can be realized by „Reference Points "and „Sensors ", of which assistance points are defined outside of the vehicle, which are firmly connected with the vehicle body. In the vehicle dynamics program CarSim can be defined thereby up to ten „Reference Points". With the help of the „Reference Points " new produced „outputs "- variables, which can be handed over to a MATLAB/Simulink program. These „outputs "- variables are the global x, y and z-coordinates of the respective „Reference Points ". These coordinates serve to be able to represent bounce or other interactions of the vehicle model with the ground. Further they can be used for the support assemblies to attach which deviate from the usual structure of a vehicle model.

The „Reference Points" are additionally used for the forces in x y and z-direction to import from MATLAB/Simulink program. These generated forces in the MATLAB/Simulink program then enter into the „Reference Points" and change the driving dynamic behaviour of the vehicle model. In order to be able to determine accelerations and speeds in the „Reference Points", in the CarSim GUI, „Sensors " surface must be provided into the respective „Reference Points". These sensors have the same x, y and z-coordinates as the „Reference Points". Additionally for the orientation, the sensor must be indicated regarding the axes of coordinates of the output coordinate system. The orientation of the axes of the sensors corresponds to those of the axes of the origin coordinate system, why the respective orientation angle is 0°. Speeds and accelerations determined by „Sensors" can be handed over likewise as „outputs "- variables to the MATLAB/Simulink program. In order to be able to examine different variants of a support assembly, additionally the variant with in each case two supports on both sides of the vehicle model was produced.

MATLAB/Simulink to Generate the Forces

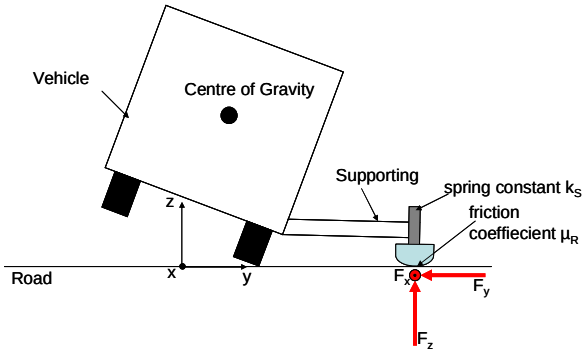

Figure 5. Schematic representation of the forces on the outrigger (supporting)

If the z-coordinate of the „Reference Points " of the supporting yields zero after tilting due to a driving manoeuvre in the frontier and thus causes a contact between the support assembly and the road, and forces are formed in horizontal and vertical direction of the supporting. The MATLAB/Simulink program is described again by the example of in each case a support per vehicle side. Horizontal forces in x and y-direction at the touching point of the support are occured (see Figure 5). These are determined according to the principle of the Coulomb friction, i.e. if the relative velocity is not equal to zero v_{rel} between two bodies at the edge contact, the bodies rub against this edge contact. Using this law frictional forces yield to :

$$F_x = -\mu_R \cdot F_z \cdot \left(\frac{v_x}{\sqrt{v_x^2 + v_y^2}} \right) ,$$

$$F_y = -\mu_R \cdot F_z \cdot \left(\frac{v_y}{\sqrt{v_x^2 + v_y^2}} \right) \qquad (1)$$

The vertical force (see Figure 5) depends on the spring constant „k_S" of the support. And „z_S" is the z-coordinate of the supportings. The vertical forces are calculated from :

$$F_z = k_S \cdot z_S \qquad (2)$$

The determination of the spring constant of the support is obtained from „the spring model of the bending beam ". A beam, which is loaded with a F force and bent, behaves mechanically like a linear course compression spring, similarly as a longitudinal beam (Figure 6) [3].

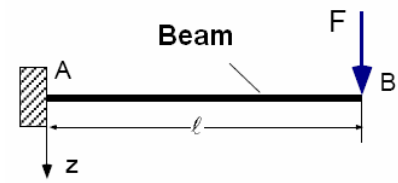

Figure 6. Cantilever with load [3]

The k_S constant of the cantilever is calculated with equation (2).

$$k_S = \frac{3 \cdot E \cdot I}{l^3} \qquad (3)$$

Because the outrigger is steel made, the elasticity module E=210000 N/mm^2. The length of the supporting arm has been chosen as l =1500 mm. And the geometrical moment of inertia I, calculated using a hollow profile to decrease the excess weight on the vehicle. To specify the spring constant the rectangular profile in Figure 7 is used.

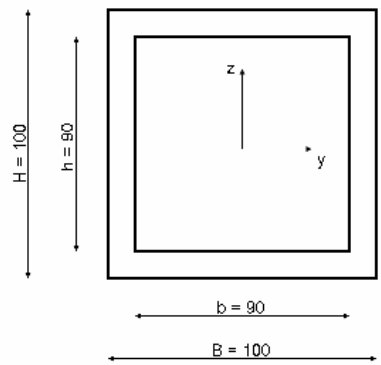

Figure 7. Rectangular profile of the supporting arm

The geometric inertial moment yields as follows:

$$I = \frac{B \cdot H^3 - b \cdot h^3}{12} = \frac{100mm \cdot (100mm)^3 - 90mm \cdot (90mm)^3}{12}$$

$$I = \underline{\underline{28,66 \cdot 10^5 mm^4}} \qquad (4)$$

As a conclusion the k_S spring constant of the cantilever results as:

$$k_S = \frac{3 \cdot 210000 \frac{N}{mm^2} \cdot 28,66 \cdot 10^5 mm^4}{(1500mm)^3} = \underline{\underline{534,96 \frac{N}{mm}}} \quad (5)$$

The frictional forces, as seen in Equation (1), are existed from the tangential velocities at the contact in the respective coordinate direction, from which are computed with also using F_z as well as from the coefficient of friction µR between the support and the asphalt. The velocities v_x and v_y on the touching points are thereby described „Sensors“ of CarSim for the MATLAB/Simulink program to hand over and be able to be determined directly.

Determination of the Friction Coefficient

The contact point of support assembly is considered to have a hemisphere of Polyoxymethylen (POM). Equation (6) has been used to determine the coefficient of friction µR of POM and asphalt.

$$\mu R = \text{Drag mass/ Total mass} \quad (6)$$

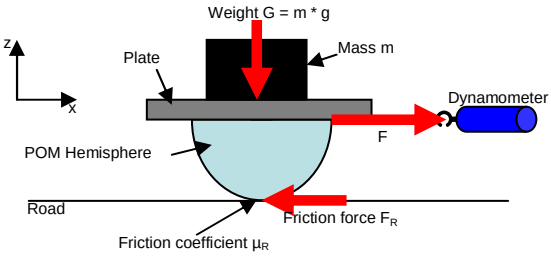

Figure 8. Specifying the friction coefficient

The experimental setup for the determination of the coefficient of friction is represented in Table 1. The mass of the steel plate weighs to m_{Platte} = 6 kg, the mass of the POM hemisphere from amounts $m_{Hemisphere}$ = 3 kg, whereby a total mass of the experimental assembly results m_{total} = 9 kg. The amount of the load on the steel plate has been changed from m = 2.5 kg to m = 10 kg in step of 2,5kg. Then the friction coefficient between the POM hemisphere and asphalt was then determined with the different weights with the help of a dynamometer, which is connected between the POM hemisphere and the steel plate on the asphalt (Figure 8).

Table 1.
Friction coefficient µR determination

Total mass m_{total} [kg]	Drag force [kg]	Friction coeffiecient μ_R
9	3.5	0.39
11.5	4	0.35
14	5	0.36
16.5	6.5	0.39
19	8	0.42
	Average:	**0.38**

Vehicle Dynamics Simulations

In order to be able to measure the influence of the supporting device on the driving dynamics of the test vehicle, different driving manoeuvres have been accomplished with different variations of the supporting device as well as different loading conditions. In this study, the results from double lane change and the step steer are presented. Table 2 indicates the coordinates of the centre of gravity (CG) of the empty vehicle and the inertia moments belonging to it.

Table 2.
Coordinates of the CG and the inertial moments of the vehicle

Coordinates	**Dimension**
x-Coordinate	1475 mm
y-Coordinate	-30 mm
z-Coordinate	840 mm
Inertia Moments	**Size**
I_x	1300 kgm^2
I_y	7300 kgm^2
I_z	6800 kgm^2

Table 3.
Variation of the influencing parameters

Driving Velocity	60km/h	80 km/h	
Loads on the Axles in % (front/rear)	1. Case 55 / 45	2. Case 46 / 54	3. Case 37 / 63
Coordinates of Loading	x = 2000 mm z = 1500 mm	x = 3000 mm z = 1500 mm	x = 4000 mm z = 1500 mm
Coordinates of Outrigger (1 supporting per vehicle side)	x = 1000 mm	x = 1500 mm	x = 2500 mm
Coordinates of Outrigger (2 supportings per vehicle side)	x_1 = 1000 mm x_2 = 3600 mm	x_1 = 1300 mm x_2 = 3000 mm	x_1 = 1600 mm x_2 = 2700 mm

In this study, loading that weighs 1000 kg has been used for the loaded conditions. The unloaded vehicle has load distribution of 60/40 (On Front Axle/On Rear Axle). The other loading variations have been given in Table 3.

Double Lane Change Results

To evaluate the dynamical driving behaviour of the vehicle, double lane change manoeuvre respect to ISO 3888-1 has been driven.

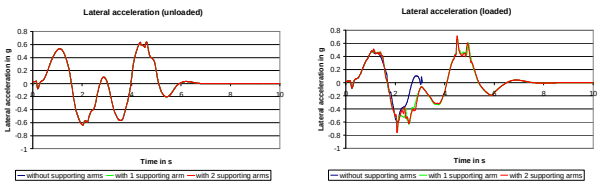

Figure 9.a. Double lane change results (FA/RA=55/45, with constant driving velocity v=80km/h) due to outrigger variation

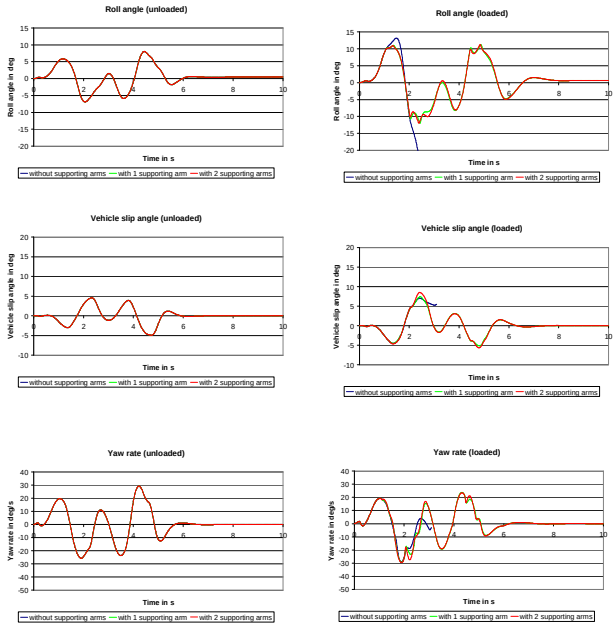

Figure 9.b. Double lane change results (FA/RA=55/45, with constant driving velocity v=80km/h) due to outrigger variation

Maximum lateral accelerations arose up to 6 m/s^2. When going back into the original driving lane as expected the highest driving dynamic demands arise. The maximally arising roll angle here is approx. 8°, the vehicle slip angle approx. 5°.Since the empty vehicle has not rolled over, there has been also no recognizable difference with variation of the supporting arms in the dynamic behaviour.

During the driving manoeuvres that have been driven loaded condition, roll angles increase due to the rising CG coordinates even with lower lateral accelerations. As soon as the steering has been entered as the input of the manoeuvre, roll angle of approx. 12° are reached, and the loaded vehicle without supporting has tilted over at approx. 2 seconds with a roll angle of more than 12°. By the integration of a supporting device to the other two simulation vehicles the roll angle is limited within the range of approx. 12°. The simulation vehicles with supporting device can be driven through the driving manoeuvre even with higher longitudinal speeds without flip over. Under the small friction value of the support assembly contact point to the ground causes no steep increases on vehicle slip angle and yaw rate, so that no critical driving conditions are to be expected here. Differences with the variation of the outrigger geometry, the vehicle dynamics responses have been in the minimal level.

Step Steer Results

The given driving manoeuvre is realized of the increasing the steering wheel angle from 0° to 150° with a speed of 500°/s [4] and the driving velocity is 60 km/h. The stationary lateral acceleration of the simulation vehicle results to a_y = 0.47 * g = 4.6 m/s^2. Further it is evident that the simulation vehicle without supporting device (blue curve) tilts over with this driving maneuver due to the high CG of the vehicle and arising lateral acceleration of approx. 5.5 m/s^2. The simulation vehicles with supporting device would drive through the driving maneuver further. The vehicle slip angle of the vehicle is minimal affected by putting the supportings, and amounted to approx. 2°, so that no driving dynamically critical conditions have been observed.

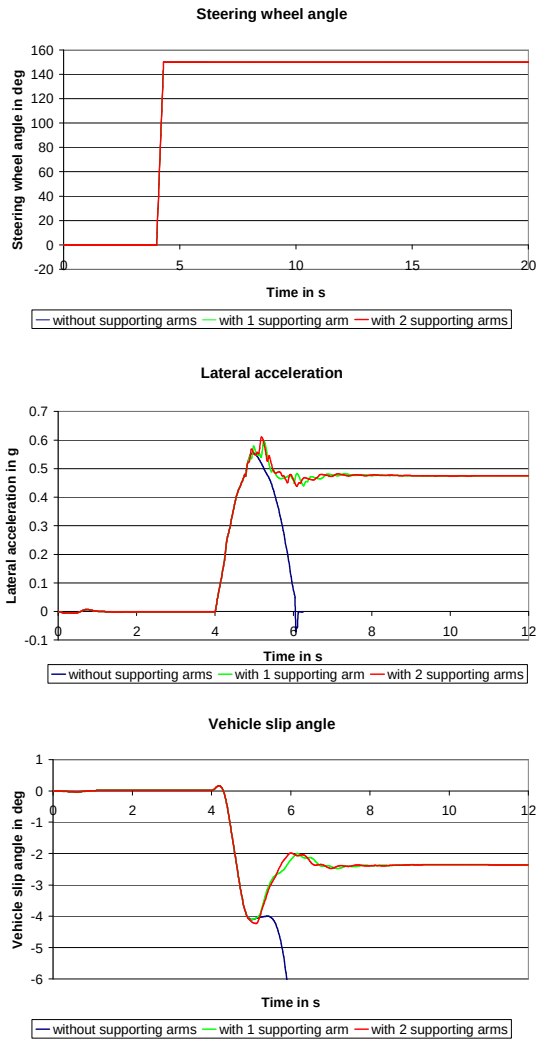

Figure 10.a Step steer results of 1000 kg loaded (FA/RA=46/54, with constant driving velocity v=60km/h)

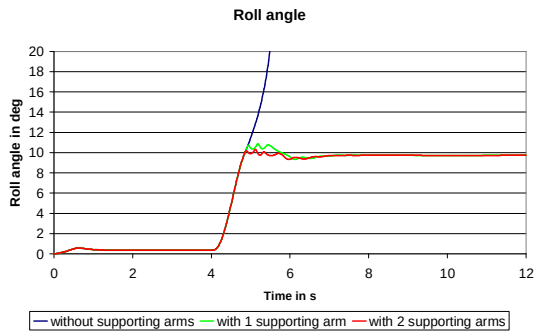

Figure 10.b Step steer results of 1000 kg loaded (FA/RA=46/54, with constant driving velocity v=60km/h)

Vehicle System Dynamics Embedding in Driving Simulator

Driving simulators nowadays find application areas intensively at both research and production, because of their capability to offer a realistic environment for the driver. In Figure 11, the Man in the Loop (MIL) system has been indicated that had been utilized for these attempts.

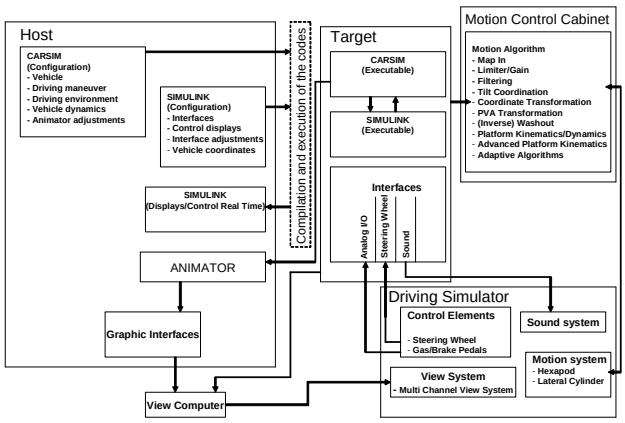

Figure 11. Closed loop system of the dynamic simulator

The operating structure of the dynamic simulator, given in Figure 11, is made up of five main components:

1- Host Computer
2- Target Computer
3- Motion Control Cabinet
4- Driving Simulator
5- View Computer

As seen in Figure 11, Host computer contains vehicle types, driving manoeuvres, driving environment, animator, vehicle dynamics; which are included in CarSim . In addition to this, host has involved Simulink for real time communication

interfaces, for control displays and to specify the vehicle coordinates.

Target computer is the platform that has the executable capability which is necessary for a real time simulation and additionally it exists interfaces for the driving simulator (for Gas/Brake pedals Analog I/O and for steering wheel CAN Bus Interface and also Sound interface for the sound system).

Motion control cabinet is the element to control Stewart platform and the linear cylinder. Kinematics and dynamics of the platform are manipulated by motion control cabinet. This component accomplishes motion algorithms and washout as well as position velocity acceleration (PVA) transformations.

Driving simulator is occupied of four constituents:

1- Control elements: Steering wheel, gas pedal, brake pedal
2- Sound system
3- Motion system: Hexapod, linear cylinder
4- View system: 3 channel animator view in the driver's cabin.

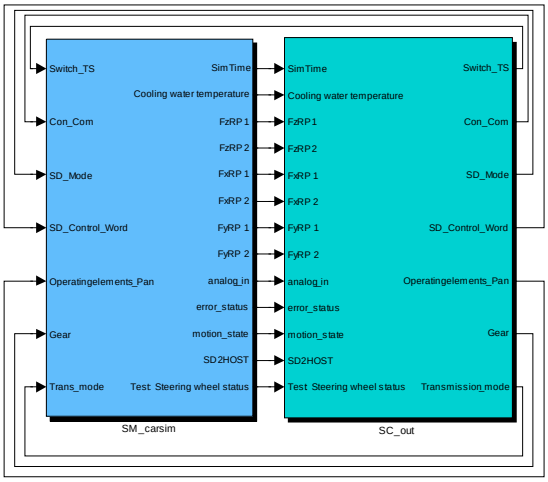

Figure 12: The uppermost level block diagram of the real time vehicle dynamics simulation on the driving simulator

In Figure 12, the real time simulation with using CarSimRT (Host computer) and RT-LAB (Target computer) is seen. The left side of this figure is called 'SM_carsim' and the right side is 'SC_out'. During the simulation the left side cannot be reached and from the right side the given parameters can be read out in real time.

Figure 13 indicates the output signals on the simulator. They are connected to the Hardware in Loop (HIL) simulation by OpComm communication blocks for the RT-LAB and respectively Figure 14 represents the input signals on the driving simulator.

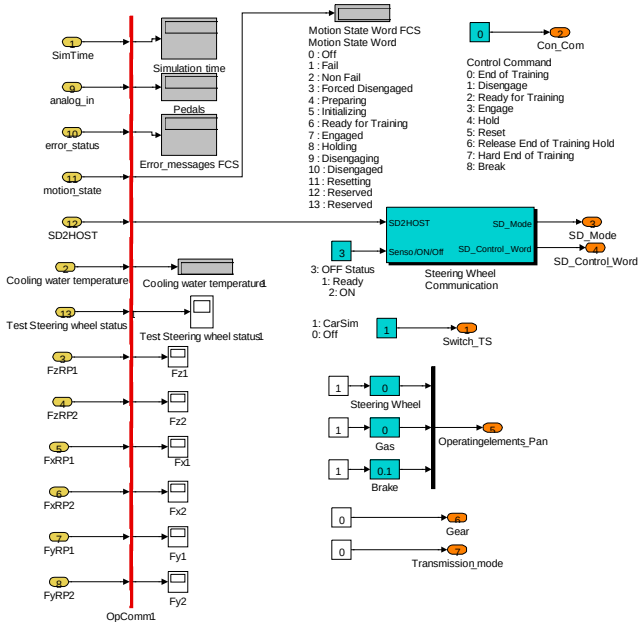

Figure 13: Block diagrams of the output signals on the driving simulator

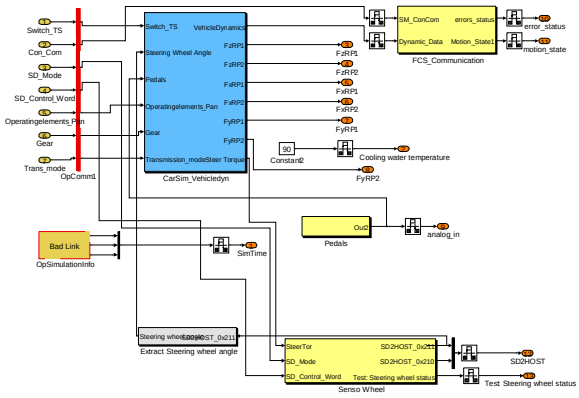

Figure 14: Block diagrams of the input signals on the driving simulator

Figure 15 represents the rollover avoidance control based on outrigger construction for the driving simulator. Here the steering wheel, gas and brake pedals are operating elements and also inputs for the CarSim S-Function as well as the forces acting on outrigger contacts (in 3 dimensions) (see Figure 5), gear and transmission mode. Within these tests, a six-gear automatic transmission mode was selected.

Vehicle dynamics from driving simulator, coordinates of the outrigger contacts (in 3 dimensions), CG (Centre of Gravity) coordinates of the sprung mass, CG accelerations of the sprung mass (in 3 dimensions), longitudinal and lateral velocities of the outrigger contacts and steering torque are outputs for the CarSim S-Function to be investigated in real time.
These outputs are fed back by rollover avoidance control based on outrigger construction calculation to CarSim S-Function as "the forces acting on outrigger contacts (in 3 dimensions)".

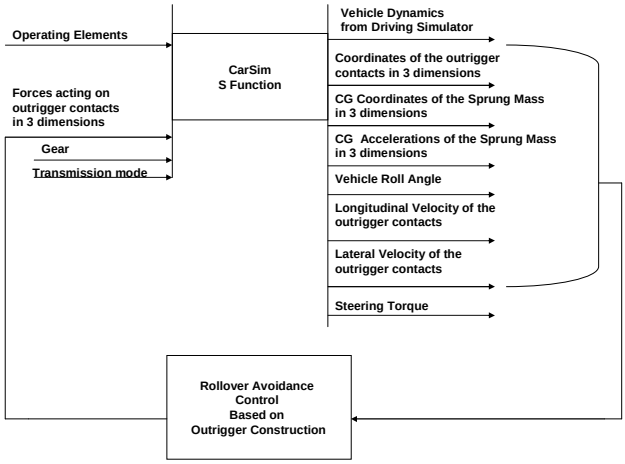

Figure 15. Block diagram of the outrigger based rollover avoidance controller

Subjective Evaluation Results

The driving attempts were accomplished on MARS (Modular Automotive Research Simulator) which is located in Automotive and Power Train Engineering, Helmut Schmidt University-University of the Federal Armed Forces Hamburg. The Figure 16 shows the operating of dynamic driving simulator.
Relating to this subjective impression assessment test, the simulator was used to represent a 7 DOF (degree of freedom) motion system, which are made up of the hexapod system and the lateral cylinder. The subjective evaluation tests that are given in Figure 17 have been realized with 12 test people who have the ages in between 23-38 and have 5 years of driving experience at least. The tests were accomplished in different conditions with double lane change (ISO 3888-1) manoeuvre with constant driving velocity v=80 km/h:

- unloaded with 1 and with 2 supporting arms per side

Figure 16: Operating of dynamic simulator MARS

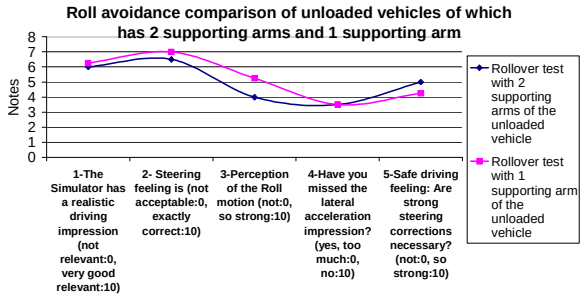

Figure 17: Subjective evaluation of the rollover avoidance during double lane change test (with constant driving velocity v=80km/h) of different variations by Questionnaire

SUMMARY AND CONCLUSION

The disadvantage of the construction shown in Figure 4 is derived from the heaviness of the outrigger than the one given in Figure 3; during the driving attempts, it cannot be loaded as much as the one with 1 supporting arm per vehicle side. On the other hand, the advantage of this configuration is that it has a larger supporting range that allows the supporting device's position to change as far as possible through the longitudinal vehicle direction depending on the centre of gravity (CG) of the vehicle. When the perception of the roll motion is compared, it can be seen that the condition with 2 supporting arms is lighter than the one with 1 supporting arm.

Figure 17 indicates that roll motion perception with 2 supporting arms has been minimized compare to the situation with 1 supporting arm. However, this yields stronger steering corrections for a safe driving.

After this study to construct an outrigger with 2 supporting arms per side has been decided because of its safety. As a further study, the likely LCV will be converted into an exact LCV. For this reason, the measuring works in the laboratory have been continued. Furthermore a database is intended to be formed which contains such vehicles like LCV, truck, sedan, SUV (sport utility vehicle) to have the common sense of how realistic the intended models are felt by the test driver when he/she drives the simulator.

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