Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/nvsd20

Roll-Over Prevention System for Commercial Vehicles - Additional Sensorless Function of the Electronic Brake System

László Palkovics , Ákos Semsey & Eduard Gerum

Published online: 09 Aug 2010.

Vehicle System Dynamics, 32 (1999), pp.285–297 0042-3114/99/3204-285$15.00

Roll-Over Prevention System for Commercial Vehicles – Additional Sensorless Function of the Electronic Brake System

LÁSZLÓ PALKOVICS[1], ÁKOS SEMSEY[2] and EDUARD GERUM[3]

SUMMARY

Recent experiences have shown that even small-medium size passenger cars face an accident which has been connected with commercial vehicles so far: the roll-over. The roll-over is the most horrible accident type for truck drivers, since he/she does not have any indication before it happens, and consequently does not react properly. This article discusses some of the problems of the commercial vehicle stability in general, and offers a solution for detecting and avoiding roll-over by using the existing sensors and actuators of electronic brake system (EBS).

1. INTRODUCTION

The most dangerous motions of combination vehicles can be classified into three groups. The first type is called *jack-knifing*, which is mainly caused by the uncontrolled large relative angular motion of the tractor and the trailer, which results in the lateral slip of the rear axles of the tractor. The jack-knifing phenomenon is one of the most common causes of serious traffic accidents in which tractor/semi-trailers are involved. The main problem with this type of stability loss is that if the articulation angle exceeds a certain critical limit, the driver becomes unable to control the motion of the vehicle by steering the tractor. Even before reaching this critical angle, the problem may become worse if the driver steers the tractor in an inappropriate direction. In solo vehicles, this accident type corresponds to the so called *spin-out.*

The second typical class of dangerous motions of articulated vehicles is the *lateral oscillation of the trailer*, which may be caused by some disturbances (e.g., side wind gust, abrupt steering effort by the driver) acting on the vehicle. When the design

[1] General Manager of Electronic Development, Knorr Bremse Hungary, Budapest, 1521, Hungary, Tel: +36-1-463 1615, Fax: +36-1-463 3978, Email: palko@sfn.knorr-bremse.hu
[2] Head of Pre-Development, Knorr Bremse Hungary
[3] Vice-President System Development, Knorr Bremse Sfn, Germany

and/or operating parameters of the system are close to the critical values, the vehicle becomes self-excited. This means that after some disturbance, the vehicle loses its stability and the system's trajectory will tend to some other limit set, which normally results in an accident.

Typical and the most dangerous commercial vehicle accident is the *roll-over*. Interesting statistical analysis was found, in which the roll-over accidents were categorised as follows (see in [1, 2]):

- *preventable*, which means that the driver would have been able to avoid the accident if a warning device had been installed on the vehicle. Only 3.3% of a total accidents were judged to be preventable;
- *potentially preventable*, which means rollover might have been prevented depending on the skill of the driver and performance of the warning device (38.4%);
- *non-preventable*, into which class the 49.7% of the total accidents were categorised; and
- *preventable unknown*, which involves only 8.6% of the total number of accidents.

These statistics prove two facts:

- a minority of the accidents might have been avoided if the vehicle had been installed with a warning system that would signal the driver to correct the vehicle's motion in some appropriate way before roll-over occurs; and
- the majority (almost 50%) of the roll-over accidents would not have been avoided with just a warning system as even a skilled driver would not have been able to control the vehicle motion behind a certain point.

By analyzing the behavior of articulated vehicles, one can observe that the driver's steering input is governed mainly by his/her reaction to the behavior of the lead vehicle unit (tractor or truck). Therefore, the behavior of the towed unit(s) (semi-trailer or full trailer) in a real closed-loop driver-vehicle system is not controlled directly by the driver. The other problem is that the vehicle driver has only a limited number of actuators (steering wheel, accelerator and brake pedal), which are not enough in all situations. The other problems are the deficiencies of the driver, as human being: delayed action, wrong decisions, or disability to control the vehicle behavior on the stability limits.

After analyzing the results of the above studies, the following main conclusions can be drawn:

1. The number of sensors in the vehicle has to be increased, or, if this is not possible, the existing sensor signals have to processed and used in different way.
2. Additional actuators have to be installed on the vehicle (sub)systems or the existing ones have to be used with other purpose.
3. If the driver is not in full control of the vehicle, the system has to support his/her action, taking action without his/her direct intention.

To fulfill the above listed requirements, several systems have been investigated and evaluated, among others the suspension control, active steering of tractor and/or trailer, hitch point control, jackknifing control and the appropriate brake control. The output of the analysis has made it obvious that the brake system has the largest potential to improve vehicle stability and also the existing system signals can be used for detection. The reason is that the tyre contact forces in any slip (both lateral and longitudinal) range can be manipulated most efficiently by using the brake system, from free rolling (maximum lateral force) up-to locking force (minimal lateral force) on any road surface.

2. ROLL-OVER PREVENTION SYSTEM IN THE EBS

As the conclusions from the previous paragraph have shown, the most appropriate actuator is the brake system (and also the cheapest one as well since it is already there), and especially in the electronic brake system the full potential can be utilised. First the electronic brake system will be introduced briefly.

2.1. Electronic Brake System

The braking performance and the behaviour during braking of passenger cars and heavy commercial vehicles significantly differs from each other. This difference in many cases has been cause for severe accidents because of different reasons: the longer stopping distance, the higher response time of air-braked vehicles, much larger kinetic energy, intention for jack-knifing are all dangerous in a traffic situations when both passenger car and commercial vehicle are involved. To reduce this gap, the electronic brake system has been introduced for commercial vehicles recently. The EBS is far more than a simple "brake-by-wire" system, besides the useful functions, it provides a good platform for future system installation. The new generation of heavy classes is assembled with EBS, and it is being introduced in the medium classes as well.

The conventional commercial vehicles, especially the medium and heavy classes use compressed air as energy source and control substance as well. The vehicle driver expresses his/her brake demand by pushing the brake pedal, and his/her demand is transmitted to the brake chambers via several modifying valve assemblies to achieve the desired brake force on the given axles. Due to this fact, the dynamics of the air flow is modified, and the system has different time constants, and is exposed to large time delays, thus the optimal control of the traditional pneumatic brake system is difficult to achieve. In addition, the system is rather complex, contains many elements, complicated lining.

The other problem is that in optimal situation the given axle brakes decelerate their own weight proportional to the actual axle load, and do not take over the job of the other axle(s). The traditional load sensing valves operate based on the static deflection of the rear suspension, but they are not able to compensate for the dynamic load transfer between the front and rear axles, which might result in locking wheels or early ABS intervention on the rear axle.

Further problem is the condition of the trailer's brakes. With bad condition brake system on the trailer the motor vehicle has to compensate for the trailer brake deficiency, resulting in higher brake lining wear, and overheating of the tractor brake system. This is caused by the incompatibility of the towing vehicle and trailer brake systems. Although the application of auxiliary (not wear) brake systems, such as drive-line retarder, engine brake, will reduce the probability of occurrence of brake fading, and results in less lining wear, their optimal operation requires certain experience from the driver. Another problem with the conventional brake system is that there is no opportunity for system diagnosis, besides the ABS self-test and the driver visual checks.

Generally, the EBS system targets on the elimination of the problems of pneumatic brake systems listed in the previous part. The basic targets are as follows:

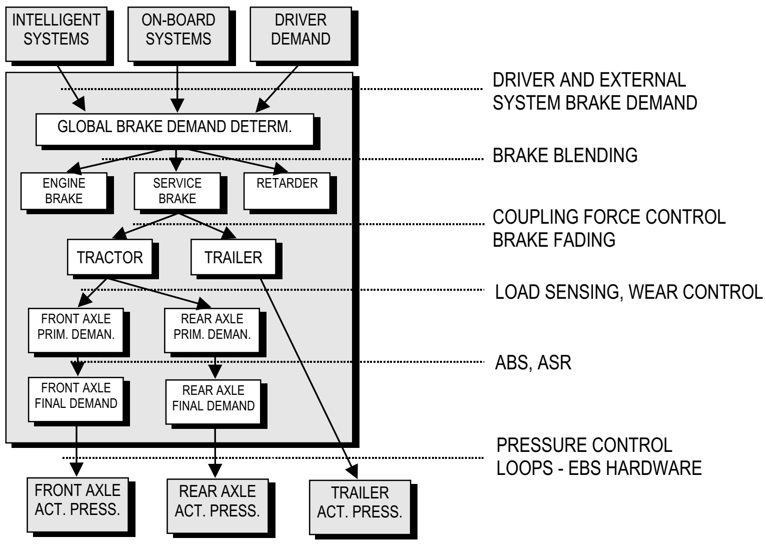

Fig. 1. Pressure level modification in the EBS.

- to keep the compressed air as energy source, but for the brake control electronic transmission is used, i.e., the driver's electronically measured brake demand is transmitted to the valve blocks, which connect the reservoirs with the brake cylinders. The time delay and the response time of the system is significantly reduced,
- more compact system will be achieved, with less component, with higher level of system integration, resulting in lower installation costs,

- the signals, necessary for the optimal control of the brake force distribution are measured electronically (rear axle load, wheel speeds, lining wear, etc.), thus more accurate axle or wheel pressure control can be achieved,
- the tractor/trailer compatibility problem is automatically handled, adapts the control algorithm to the trailer, and controls the brake pressures accordingly,
- resulting from the above features, the EBS is a safer, better performing brake system with reduced stopping distance and enhanced braking stability,
- provide a platform for future systems, such as adaptive cruise control (ACC), radar brake system, drive stability control system.

At the moment, there is no unique EBS philosophy (unlike for ABS), there is no industry standard. The available systems differ from each other in the component arrangement, but the system layout, control philosophy, data transmission, back-up principles, and functionality is very similar. The basic systems available in the market are described in [3], [4], [5].

Figure 1 shows the levels of pressure modifications in the EBS, explaining the EBS operation. From the driver input, and some other autonomous system input the global brake demand is calculated, which is split among the non-wear brakes (retarder, engine brake) and the brake system itself. This, so called "brake blending" can download the wheel brakes, keep them cool for emergency situations. On the next level, the CFC (coupling force control) decides how to proportion the brake demand between the tractor and trailer. On the motor vehicle further modification will be achieved by the load sensing compensating for the load transfer between the front and rear axles, and at partial braking the wear control algorithm can also modify the pressures at axles. The brake pressure produced by the axle module can finally be modulated by the ABS and ASR system. This pressure calculation flow will be disturbed by the ROP as well as the Drive Stability Control System.

2.2. Roll-Over Prevention System in the EBS

Based on the results of the accident analysis, the following two major findings can be derived: (1) the roll-over danger has to be recognized in good time by means of vehicle assembled sensors, and (2) the occurrence of roll-over should prevented. To achieve these two findings, although they sound not very complex, at the actual, mostly economical circumstances, is not very easy. Installation of roll-sensor on the vehicle, either on the towing or on the towed vehicle unit is not very feasible, and there is a lack of suitable sensors.

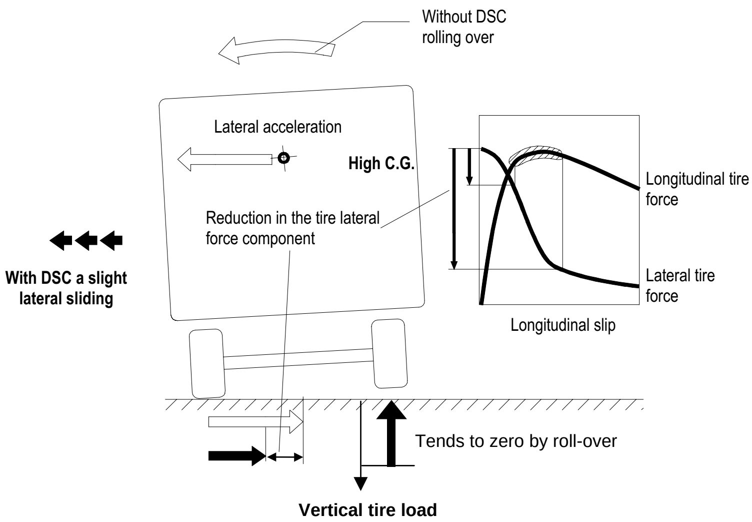

Fig. 2. Physics of the vehicle roll-over.

One problem is the physics of the roll-over, which is depicted in Figure 2. The roll-over of a vehicle starts when the tire-road contact force on one of the curve-inner side wheels becomes zero. This situation has to be detected or measured, however, a force transducer for measuring the vertical wheel load is not available or feasible (there exist tire-tread built sensors for measuring the tension in the tire tread for slip calculation, but they are expensive and not really applicable). The roll-over responsible pair-of-force arises from the high lateral inertial force and its counterpart on the road, which is generated by the tire, the lateral force component. If the cg point position is high, the resulted moment is also large and can result in roll-over. From this it can be seen that only by means of the controlled suspension the prevention of roll-over is not possible, since it cannot reduce the lateral tire force component, the only (mostly theoretical, since it cannot be achieved by air suspension) effect is to keep the vehicle body perpendicular to the road, thus eliminating the rolling torque of the gravitational force.

The basic idea of the Knorr Bremse patented ROP® system is if one cannot sense the vertical wheel load directly, one has to find another quantity, which is in strong relationship with the previous one. In the case of a brake system supplier, the straightforward solution is the brake or traction force, since if there is no vertical load, the brake or traction force cannot be generated either. This finding resulted in a system, which stimulates the brake or throttle system by using of a small effect (braking or throttle reduction) if the calculated lateral acceleration exceeds a certain limit value (e.g., 0.4g deceleration, which is considered to be high in case of the commercial vehicles), and if this small effect results in high slip difference between the two sided wheels, that means that a given wheel is about to loose contact with the road.

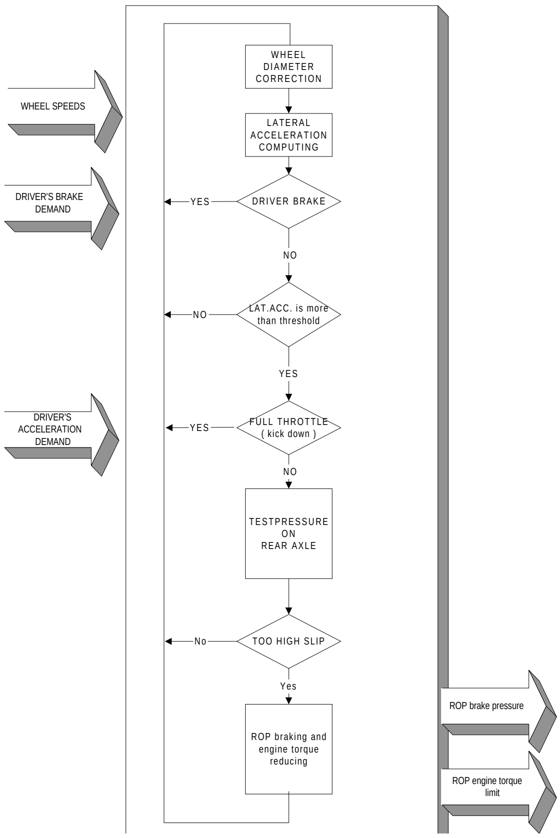

Fig. 3. Block diagram of the ROP® algorithm.

The described procedure gives the only direct indication of the wheel lift-off.

For the prevention also the brake system is used, since, as seen in Figure 2, the roll-over responsible pair of force has to be reduced, which means the reduction of the lateral inertial force by means of speed reduction with the combined reduction of the lateral force component by means of manipulating the tire slip according to the figure. These two effects together are enough to prevent roll-over on both a combination and also on a solo vehicle.

As Figure 2 shows, normally the braking of the wheels until the ABS becomes active is enough to reduce the lateral tire force, in some vehicles there is no other option. The (nearly) full locking of the wheels would have much more significant effect, however, in this case the system requires more sensors, and should operate in the DSC environment, as discussed in paragraph 2.3.

The major advantage of the ROP® system is that it does not require any additional sensors to the EBS, since it uses for detection only the existing wheel speed sensors and for actuation the wheel brakes. The product itself is “nothing more” than a software, however; the safety aspects of the system are very complex, the original EBS safety management has to be modified significantly.

Figure 4 shows a series of comparison tests with a single vehicle and the operation steps of the ROP® system during a severe lane change maneuver (moose test). The left column shows the passive vehicle, while the right column shows the vehicle with ROP® system activated. On the upper left chart the load transfer has already happened on the rear axle, while at the same time on the right hand side the ROP® has made the brake system stimulation for detection. In the middle left picture the rear axle inner wheel has left the ground, while in the right side the ROP® has braked the vehicle. In the lower pictures the result is shown: the passive vehicle is travelling on the outtriger with two wheels in the air (practically has rolled-over without the protection wheel), while the controlled one has reduced the vehicle speed to a safe level, the roll-over has been avoided.

2.3. Drive Stability Control System as Extra Function to the EBS

As was mentioned earlier, the sensorless ROP® system operates the wheel brakes within the normal ABS slip range. However, the system cannot go above that since it will have no information on the actual behavior of the vehicle, although sometimes it would be desirable.

Figure 5 shows the action mechanism of the Drive Stability Control system. One has to note the priority of DSC with respect to other controlled system. As seen, the DSC can overrule the ABS desired wheel-slip and pressure, if the controller decides so. The reason is that DSC uses additional sensor information, which is not available in the EBS. These sensors are as follows:

- Steering wheel angle sensor, transmitting the driver’s demand on direction,
- yaw rate sensor on the towing vehicle,
- longitudinal and lateral accelerations.

These signals provide enough information on the vehicle behavior for DSC controller to compute the actual and desired behavior of the vehicle. If these two values differ from each other in larger extend than a certain pre-determined threshold, the DSC brakes one or other wheel on the vehicle.

Figure 6 shows two typical situations. In Figure 6a the vehicle negotiates a curve but with too high speed, and the combination slides out of the road, showing a understeered handling characteristic. The reason for this behavior is that the lateral control force on the front axle is not high enough to provide the necessary torque. To compensate this, the DSC system brakes the curve-inner rear wheel, thus producing the necessary torque. Similar happens, when the vehicle leaves the curve in Figure 6b.

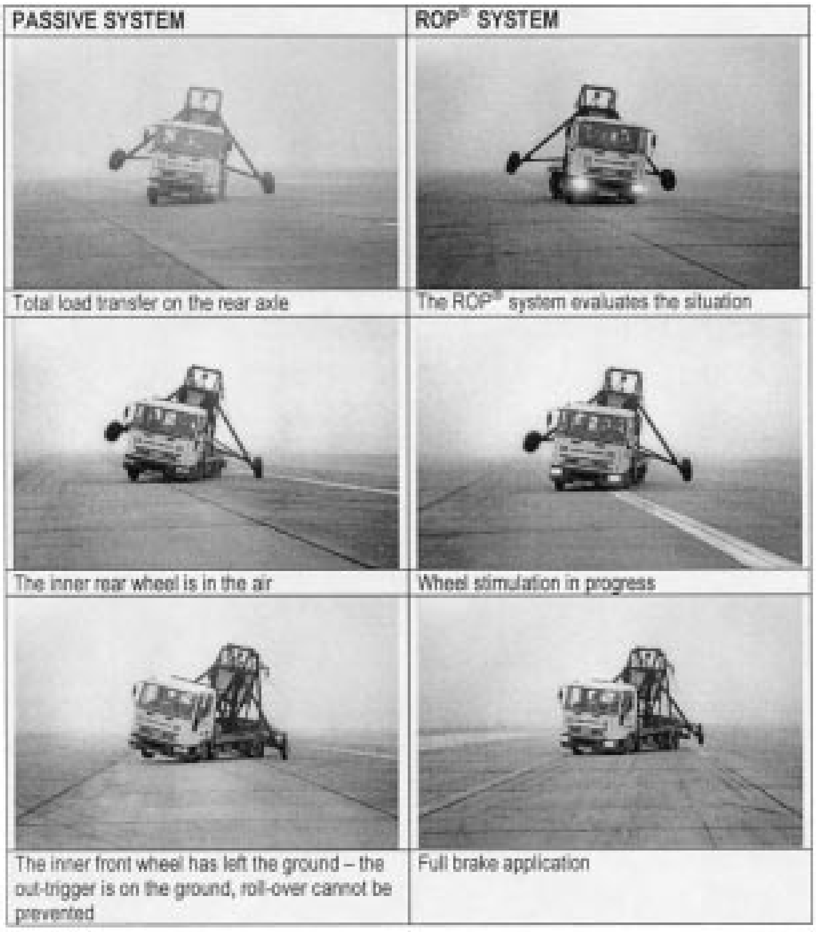

Fig. 4. Sudden steering maneuver with/without ROP® system.

A quantitatively different situation is shown in Figure 7. Figure 7a depicts a situation when the driver accelerates while cornering. Due to this, the force balance between the front and the rear axle is destroyed, and the too high lateral force on the front axle results in a moment, which spins the vehicle out, or in case of combination causes jack-knifing. In addition to this, the trailer can push the motor vehicle via the king-pin, which makes the situation worse. The controller's action is that by means of increasing the slip on the curve-outer front wheel he reduces the lateral force component, and, at the same time, brakes the tractor's outer-rear wheel until a certain slip

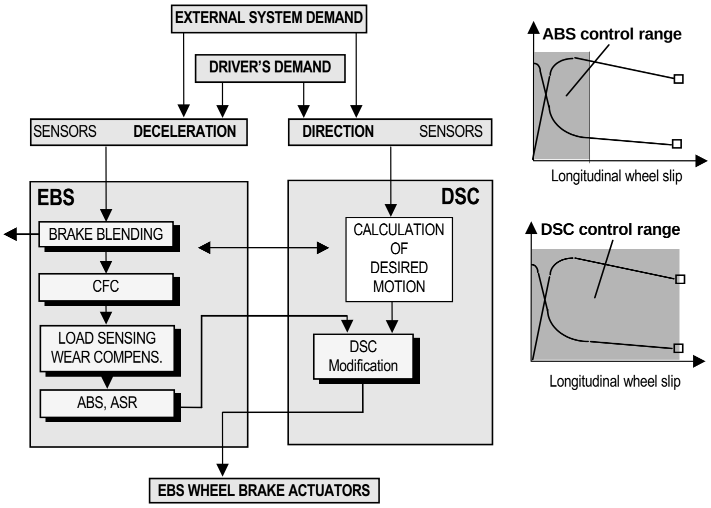

Fig. 5. The DSC system action mechanism.

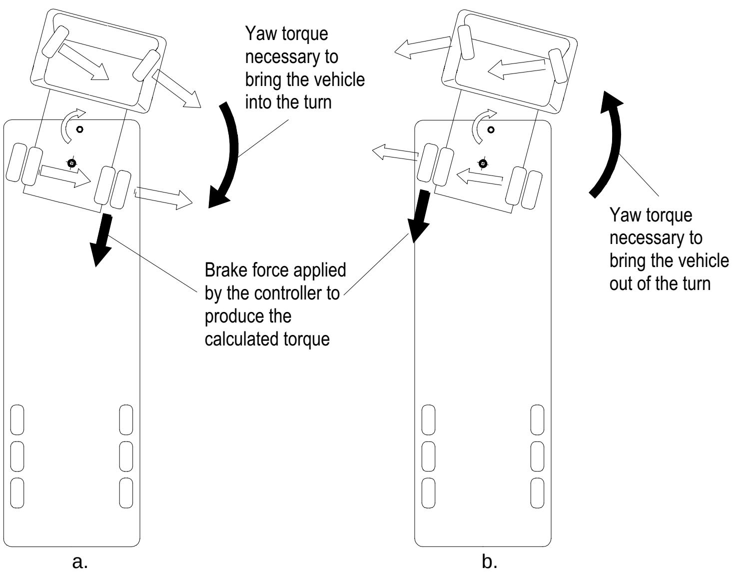

Fig. 6. DSC intervention when the vehicle is slightly understeered (a) When going into a turn (b) When leaving a curve.

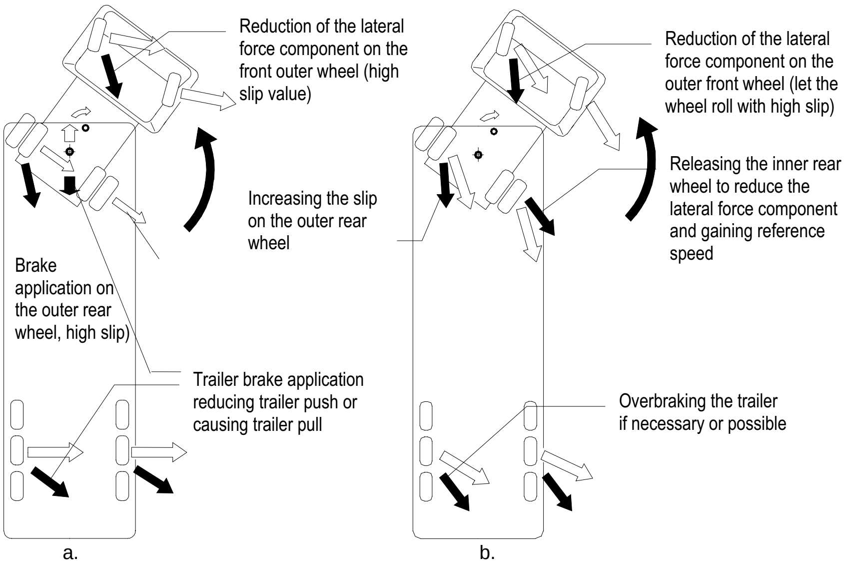

Fig. 7. DSC intervention when the vehicle is slightly oversteered (a) During cornering and accelerating (b) During combined cornering and braking.

value producing additional torque. If the trailer is coupled, the trailer brake will also be actuated producing pulling force at the king-pin. A similar event occurs during braking while turning; if the combination starts to jack-knife, the DSC produces high slip on the outer-front wheel thus reducing the lateral force component.

As can be conducted from the above analysis, the appropriate wheel-slip control is the most important part of the DSC control. The graphical representation of the stabilizing torque optimization task is shown in Figure 8. The brake-modified force vector produces the stabilizing – additional – torque, which is proportional to the territory of the shaded triangles shown in the Figure. As seen, there is no problem on the front axle, since any force produces a positive, stabilizing torque, only the optimum has to be found, which is reached practically at maximum slip (locking wheel). The conflict is on the rear axle, since if the slip is higher than a certain value, which is the limit force vector, the resulted torque will start acting in the opposite direction, which has to be avoided. Therefore, a very careful slip control has to be realized on the rear axle.

From the above analysis it can be seen how the DSC system acts mainly on low friction road. The question is, how the DSC acts during the so-called famous moose-test, which is a severe lane change maneuver with high speed, and can be dangerous also for passenger vehicles on dry road, or in any roll-over dangerous situation. Figure 9 shows series of actions what DSC system takes during this maneuver.

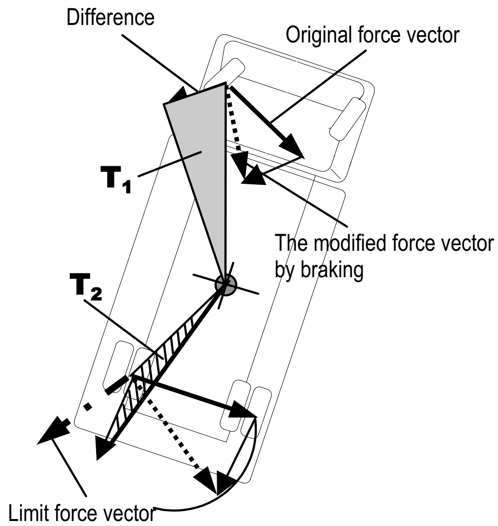

Fig. 8. Graphical representation of the DSC's slip control algorithm.

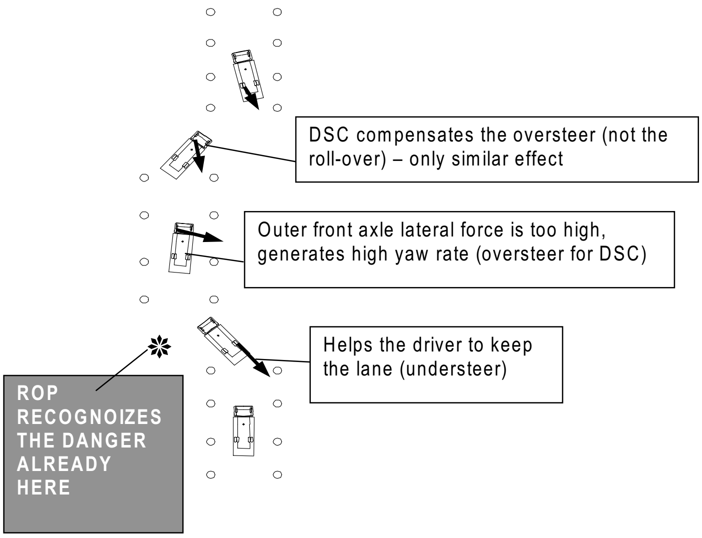

Fig. 9. Action mechanism of the DSC system during the moose-test.

The first DSC intervention happens after negotiating the first curve of the maneuver. Here the DSC recognizes that the vehicle behaves in understeered manner, and helps the driver to follow the desired route. When the vehicle starts to return to the original lane, the vehicle starts to slightly spin out, since the vehicle speed is too high, and too high load will be generated on the curve-outer front wheel, which results in high lateral force. This lateral force is responsible both for the spin-out, and for the roll-over. The DSC system does not know about the roll status of the vehicle, but evaluates this situation so if it would be a oversteered case, and thus brakes the outer front wheel, which results in reduced lateral force. Although the intention is not the same as in case of the ROP® system, the effect does not differ.

As can be seen from the above analysis, both systems provide the optimal control in case of roll-dangerous situation, but to realise this function, the ROP® does not require extra sensor and as effective as the DSC system.

3. CONCLUSIONS

The EBS alone gives much more functionality to the brake system compared to the conventional pneumatic system, improving driving comfort and generally vehicle safety by shortening the stopping distance by means of reducing of system's reaction time, and improves ABS functionality. However, EBS does not influence significantly the directional, lateral and roll dynamics of the vehicle, but offers a good platform for installing systems such as drive stability control (DSC) and ROP®. The most exciting function of the EBS is the ROP®, which does not require extra sensor to the existing ones only modification in the control software, but offers significant increase in the vehicle roll stability.

ACKNOWLEDGEMENT

The development work is being supported by the Hungarian Science and Research Foundation under contract numbers OMFB-06302970204, OMFB-06302970203.

REFERENCES

1. Glasner, E.Ch. (1994) "Active Safety of Commercial Vehicles", *AVEC'94*, Japan, Tsukuba, 24-28 October 1994, pp. 9-14.
2. Sparks, G.A., and Berthelot, C. (1989) *The Cost/Benefit Analysis of a Rollover Warning Device for Large Trucks*, Sparks and Associates Ltd., Saskatoon, Saskatchewan, June.
3. Bassi, M. (1996) "Electronic Braking System: Present and Future Developments", *IMechE Seminar Publication 1996-14*, Symp. Electronic Braking Systems, seminar paper.
4. Incardona, M., Moore, K.R. (1996) "Electronic Braking Systems – Truck Manufacturers' Expectations", *IMechE Seminar Publication 1996-14*, Symp. Electronic Braking Systems, pp. 1-7.
5. Wiehen, C., Neuhaus, D. (1996) "EBS – Ready for Introduction", *IMechE Seminar Publication 1996-14*, Symp. Electronic Braking Systems, pp. 10-23.