STATE-OF-THE-ART AND FUTURE DEVELOPMENTS IN INTEGRATED CHASSIS CONTROL FOR GROUND VEHICLES

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Abstract

Many modern ground vehicles feature state-of-the-art powertrain, braking and suspension control systems. These technologies are rapidly filtering through to heavy and off-road vehicles. The drawback of many of these systems is that their operation is largely considered only in stand-alone mode. The paper introduces up-to-date and coming ground vehicle technology related to the integration and advanced control of active chassis control systems. In particular, addressing the task of coordinated subsystems control can provide simultaneous enhancements in traction and braking performance, handling, off-road mobility, driving comfort and energy efficiency. A special focus in the paper is given to coordinated operation of brake control, active suspension, and dynamic tyre pressure management. The influence of each particular subsystem on the vehicle safety, off-road mobility and ride comfort is evaluated in simulation. It is further described and confirmed in simulation how the integrated chassis control (ICC) can simultaneously improve each of these vehicle characteristics. From the hardware viewpoint, a variant of ground vehicle architecture with aforementioned integrated active chassis systems is introduced. This architecture and its corresponding implementation on a sport utility vehicle are currently investigated within the European Union-funded Horizon 2020 consortium EVE. The work presented is a collaborative effort among several ISTVS members across the globe.

Keywords: integrated chassis control, vehicle dynamics, brakes, active suspension, tyre pressure control

1. Introduction

Development of an integrated active chassis systems responsible for simultaneous improvement of handling, stability, braking performance, energy efficiency, ride comfort and other vehicle properties is one of the most challenging research domains in control of ground vehicle dynamics. Basic works in this area have originated in the middle of 1980s. In particular, Fruechte and co-authors have introduced in [1] the results of General Motors project *Trilby*, where a global integrated architecture for various vehicle subsystems has been developed, Fig. 1. Beneficial effects of integrated chassis control on ground vehicle dynamics consist first of all in increased utilization of tyre-road friction and enlargement the area of stable vehicle motion. This statement can be illustrated with GG diagrams (longitudinal vs. lateral acceleration). In particular, Fig. 2 displays effective areas of the GG diagram by operation of singular active chassis systems (as proposed by Yamamoto in [2]) and then Fig. 3 shows the impact from the system integration (as proposed by Sato et al. in [3]).

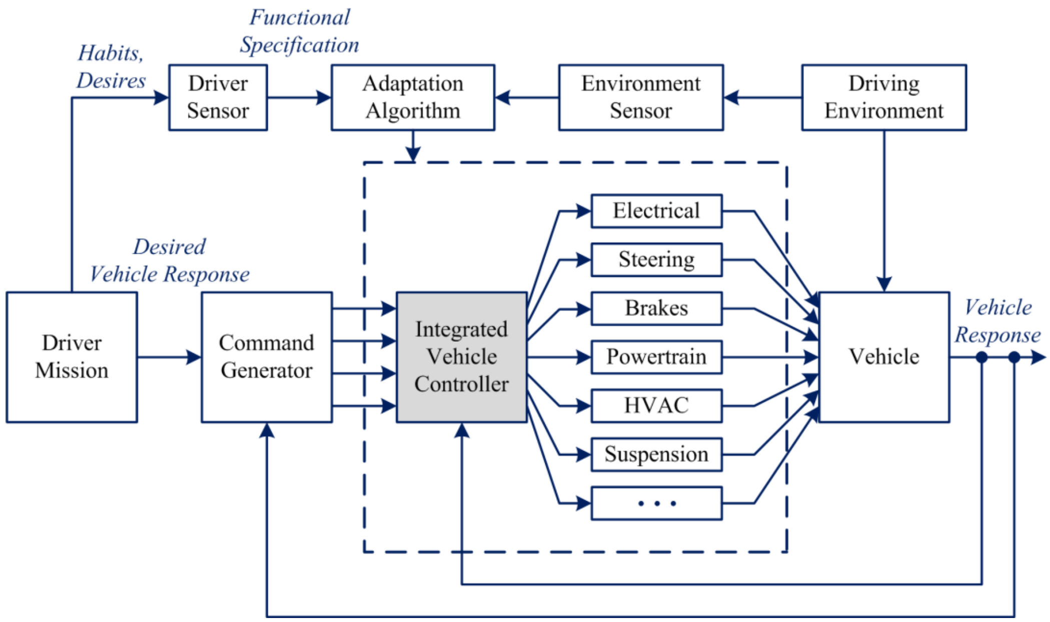


Fig. 1. *Integrated control with driver and environmental adaptation (adapted from [1]).*

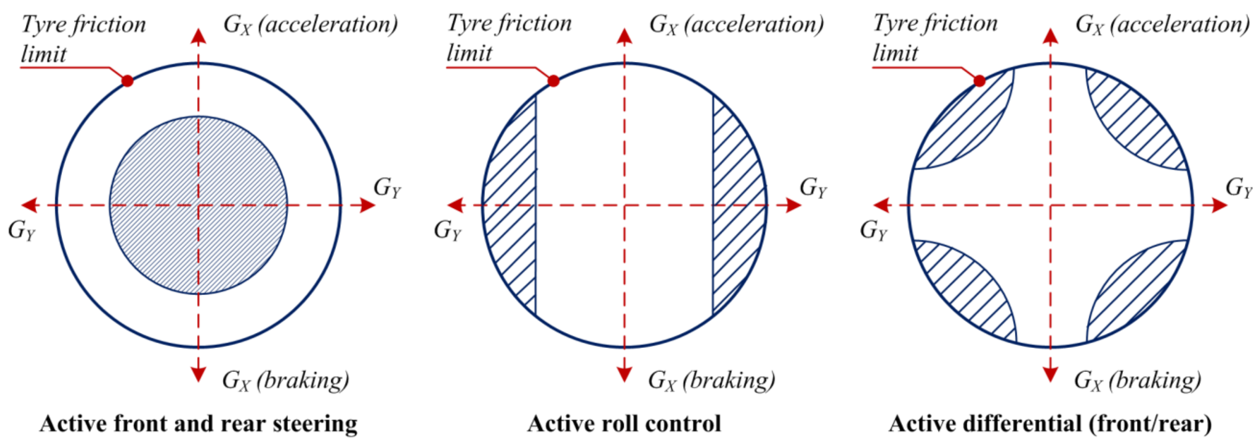


Fig. 2. *Examples of effective range (shown as hatched regions) of different chassis control systems.*

It can be concluded from Fig. 2 and Fig. 3, that a stand-alone operation of active systems contributes to some extent to the enlargement of the tyre friction utilization as compared with the vehicle motion without control systems. The integration of several individual active systems improves effectiveness and allows, in an ideal case, the maximum use of the tyre friction up to limits determined by actual surface conditions.

Analysis of technical and scientific publications points out that the most widespread combinations of integrated systems includes (i) active steering and suspension control, (ii) active steering and brake control, (iii) active steering and yaw rate control, and (iv) active suspension, steering, brake and driveline control [4]. Recent studies also propose advanced variants of Integrated Chassis Control (ICC), where, for instance, active control of camber angle or tyre pressure is used [5]. It should be mentioned that most of the known engineering solutions for ICC are beneficial for driving safety. Most of the studies are related to the cases of curvilinear motion, whilst the longitudinal vehicle motion in terms of subsystems integration is rarely explored. Also the potential of the ICC for improvement of such vehicle characteristics as ride and driving comfort are usually not considered. Integration of the active chassis systems is especially relevant for ground vehicles specified for off-road operation because the ICC could also efficiently contribute to the improvement of terrain mobility characteristics.

In line with statements introduced above, the presented paper contributes to further development of the integrated chassis control as applied to ground vehicles operated both in on-road and off-road conditions. The structure of the paper is as follows. First a brief survey of studies dedicated to the integration variants of active chassis systems for ground vehicles will be discussed. Then a new concept of the ICC system for a sport utility vehicle (SUV) will be presented. This concept realizes the integration of individual wheel brake control, dynamic tyre pressure management and active suspension. Influence of each subsystem operation in stand-alone mode on vehicle safety and ride comfort is evaluated considering performed simulations and recent studies. The performance of the proposed integrated control is illustrated with SUV simulation results for the case of emergency straight-line braking considering typical off-road with following surface types: (i) smooth road, (ii) Belgian paving and (iii) angled corrugations.

The discussed ICC concept is now under development within the framework of the research and innovation project EVE involving ISTVS members from different countries.

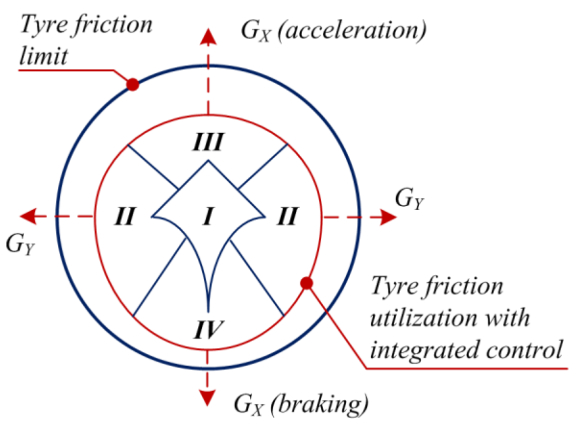


Fig. 3. *Influence of integrated chassis control systems on tyre friction utilization. Regions: I - without control; II - integration of active suspension and active front and rear steering; III - integration of traction control and active front and rear steering; IV - integration of anti-lock braking control and active front and rear steering.*

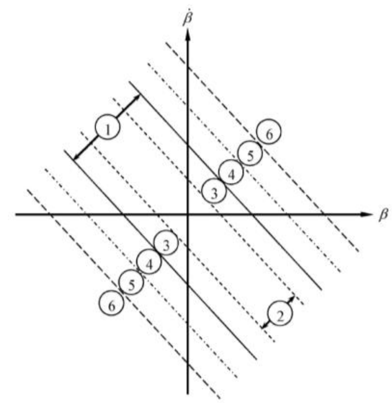


Fig. 4. *Different regions in "β - dβ/dt" phase plan for the rule based integration scheme (reproduced from [6]); 1 - reference region for control design, 2 - active steering inclusion for steerability improvement, 3 - transitions between control tasks, 4 - active steering inclusion for stability improvement, 5 - active driveline inclusion, 6 - active braking inclusion.*

2. Overview of Integrated Chassis Control for Ground Vehicles with Off-road Capabilities

One of the main, experimentally confirmed, advantages of the ICC lies in the improvement of the vehicle stability. Therefore, in the case of conventional road vehicles, the corresponding control task is basically focused on the keeping of yaw rate $d\psi/dt$ and side slip β in specified safety limits. This can be illustrated in Fig. 4 showing the "β - $d\beta/dt$" phase plan. It can be seen here that initially only active steering is included into the integrated control chain. Then, when an actual driving situation becomes more critical, subsequent activations of the active driveline and the active braking take place. However, for sport utility vehicles and generally for ground vehicles operation in off-road conditions, the vehicle stability in terms of the rollover prevention is of more significance [7].

Several studies have demonstrated that the rollover stability of SUVs and light off-road vehicles can be supported, within certain limits, by Electronic Stability Control (ESC) systems through individual wheel torque modulation in braking or traction mode [8, 9]. Nonetheless, the stability control solely through the ESC system may demonstrate restrained performance in complex driving situations, for instance, on a rough surface. In particular, the braking mode of the ESC system is required for the stability control, but a conventional brake torque modulation algorithm is occasionally being deactivated to avoid the wrong wheel slip definition caused by faulty operation of wheel speed sensors due to considerable wheel oscillations on the rough surface. Another conceivable example of insufficient application of the ESC is the multicriterion control task, when it is simultaneously required to guarantee the rollover prevention and to maximize mobility characteristics like vehicle velocity or tyre friction/adhesion utilization.

Next reasonable variant of improving the rollover stability is the use of active systems influencing the vertical load that can be principally realized through active suspension control [10, 11]. Of course the applicability of the active suspension for stability control tasks can be also considered within certain limits defined both by driving comfort and safety.

The described limitations of stand-alone active systems substantiate the motivation for the integrated chassis control. It can be also illustrated with several recent studies for SUV / off-road vehicles. For instance, the work [12] has introduced results of joint operation of the differential braking (yaw moment control) and the active suspension. The integrated controller is based on the robust linear quadratic regulator with the objective function considering variation of longitudinal and vertical tyre forces. Corresponding simulation results have shown that the proposed controller can sufficiently contribute to rollover prevention. In particular, for a fixed fishhook maneuver with the steering wheel angle of 221° at 80 km/h, the rollover speed has been increased by 52% as compared with the same non-controlled maneuver. Such an effect is also demonstrated in the study [13] describing the integration of the ESC with the active suspension on the basis of the optimal control technique. For the ESC, the controller uses the reference yaw rate and minimization of sideslip angle. For the active suspension, the logic is based on the minimization of the performance index including heave, roll and pitch accelerations of the vehicle, and deflection of the suspension and tyres. The advantages of the integrated control have been shown with the simulation of obstacle avoidance and fishhook manoeuvres: the roll and pitch angles, as well as the heave position of the vehicle were kept close to zero during the obstacle avoidance. For the fishhook manoeuvre from 100 km/h and maximum steering wheel angle up to 55°, the integrated controller has reduced the rollover index from approx. 0,25 (as for passive manoeuvre) to 0,1.

Comprehensive variants of the system integration include more than two subsystems and therefore can bring versatile, multicriterion improvement on the vehicle dynamics. In this context the study [14] has investigated simultaneous operation of the brake-based electronic stability control system, the torque vectoring and the active front steering for an off-road truck with a full mass of 10 t.. The model-in-the-loop (MIL) and hardware-in-the-loop (HIL) simulation results for a maneuver of pathway changing by driving on soil road with the friction coefficient $\mu=0.6$ have demonstrated that the joint control of all three mentioned subsystems during such a maneuver gives a combined effect in (i) minimization of misalignment between reference and actual yaw rate on 36,7%, and (ii) reduction of slip power on 31,9...32,8% as compared with the combinations "ESC + torque vectoring" and "ESC + active front steering". However, the results have also indicated necessity in further optimization of the control distribution between individual subsystems because, for example, non-tuned operation of all three subsystems (each subsystem contributes 1/3 of total control effort) has led to loss of longitudinal velocity of 7.2 %.

The problem of proper coordination of three and more active systems within the framework of the integrated control is also illustrated by other studies, and different methodologies are being proposed for this purpose. In particular, the work [15] has investigated the global chassis control involving ESC, torque vectoring, active roll control through varying the anti-roll bar stiffness, and active differential. The corresponding integration procedure is realized using a rule-based approach for consecutive inclusion of individual subsystems or switching between them. For example in the case of the yaw dynamics control the system states are as follows: (i) If the requested correcting yaw torque can be generated by the active differential only, then ESC and TV systems are deactivated; (ii) If the requested correcting yaw torque cannot be fully covered by the active differential, then the active differential still generates the maximum torque and the rest torque is equally generated by the ESC and TV (share of 50% for each system) under conditions that the vehicle velocity should not be changed; (iii) If it is not possible to keep the vehicle velocity and to correct yaw dynamics simultaneously, the share of ESC control is increased to generate required yaw torque in spite of possible velocity reduction. Hence, such an approach considers both criterion of vehicle performance (velocity) and safety (yaw dynamics) during the control process and tries to minimize the losses in performance (velocity reduction) by simultaneous ensuring the vehicle stability. A more complex and robust method is proposed in [16], where the joint operation of active steering, active suspension, dynamic tyre pressure management, active camber control, brake control and traction control (through electric motors) is realized using the control allocation. The corresponding algorithm of subsystem coordination is based on restriction weights into the control allocation. During the maneuver the restriction weights are corrected in accordance with the performance criteria characterizing energy consumption and energy losses both in relation to the vehicle and its components like tyres.

The configuration of the integrated chassis control introduced in previously mentioned work [16] points to the renewed interest and increased demand for the inclusion of new types of active systems, which are focussed on the control of specific parameters (camber or toe angles, tyre pressure, tyre stiffness) influencing the tyre-surface contact forces. Such examples as the active camber control or the dynamic tyre pressure management can be considered as newcomers in ground vehicle engineering and are rarely investigated in practice. Their main purpose is to support the operation of conventional vehicle control systems like ESC, torque vectoring or active steering through possible modification of tyre-surface contact area. In particular, examples of the active systems under discussion are described in [17, 18] for the camber control and in [19, 20] for the dynamic tyre pressure management. The integrated chassis control with the mentioned subsystems is of special interest for off-road mobility because it opens new tools for targeted influence of tyre-pavement interaction parameters.

The studies discussed above are mostly related to the lateral vehicle dynamics and cover rarely the cases of straight-line manoeuvres. Nevertheless, some publications have described advantages in the use of the brake system integrated with active suspension. Based on a set of simple control rules, an integration of such systems during emergency braking brings effect of 4-5% braking distance reduction without deterioration of ride comfort [21]. Even more effect was achieved by the use of the active suspension and anti-lock braking system in [22], where the reduction of braking distance achieved 15% for the on-road conditions. Several recent investigations also point to advantages of the combined active suspension / brake control for the longitudinal vehicle dynamics in the case of the vehicle operation on a rough surface. In particular, the study [23] has presented results of multi-body modelling of the SUV equipped with the integrated controller of ABS and four-state semi-active suspension system. It has been shown for the straight-line braking from 70 km/h that the variation of suspension settings allows reducing the stopping distance on the Belgian paving by up to 14 m as compared with conventional ABS braking and fixed spring and damping settings. The same effect in the stopping distance reduction has also been observed for the surface with the parallel corrugations: up to 1,9 m by braking from 80 to 10 km/h [24].

This introduction and short overview of the integrated chassis control (ICC) for ground vehicles with off-road capabilities presented in this study allows drawing several conclusions:

- The main effect in ICC operation can be reached in the support of the vehicle stability and, especially in context of off-road vehicles, rollover prevention and braking performance;
- Reasonable subsystem combination for rollover prevention and improvement of longitudinal vehicle dynamics should include individual wheel torque control and elements of active suspension at least;
- Further improvement of ICC performance can be expected by inclusion of additional active systems influencing tyre-surface contact interaction parameters;
- Efficient integrated chassis control has to include several performance criteria related to the ground vehicle stability, safety, mobility parameters and ride comfort.

These conclusions will be substantiated in the following sections by presenting a concept of the ICC for an SUV with off-road capabilities. The ICC is especially developed for the rarely explored case of longitudinal vehicle motion where traction/braking performance and ride comfort can be improved compared to vehicles with conventional chassis control systems.

3. Concept of Integrated Chassis Control Focused on Longitudinal and Vertical Dynamics of Ground Vehicle

The ICC concept introduced in this section is being experimentally investigated within the framework of the project *EVE - Innovative Engineering of Ground Vehicles with Integrated Active Chassis Systems* - funded by the European Commission and uniting eleven partners from Germany, Spain, Belgium, The Netherlands, Sweden, South Africa and USA, namely TU Ilmenau, Tenneco Automotive, University of Pretoria, Gerotek Test Facilities, TU Delft, SKF Automotive, Chalmers University, Virginia Tech, dSPACE, Instituto Tecnológico de Aragón, and ESTEQ. One of the main targets of the project EVE is to advance the state-of-the-art ICC methods applying them to off-road vehicles. Part of the strategy to reach this target is to illustrate the newly developed techniques from the EVE project on an SUV demonstrator based on a Range Rover Evoque. The ICC architecture under development for the SUV demonstrator is depicted in Fig. 5 and integrates three major tools: the electro-hydraulic brake control system (EHB), the tyre pressure control system (TPCS), and the vertical dynamics control system (VeDCS).

The brake torque controller is responsible for the base brake and ABS control functions. The system has a decoupled electro-hydraulic configuration. Instead of direct coupling between the driver actuation and wheel brakes the driver's demand is measured by the pedal travel sensor and transmitting the signal to the *brake torque controller*. To guarantee required brake pedal feel, the embedded pedal simulator provides the force feedback to the driver. The brake pressure p_{br_est} is numerically estimated in the brake controller. In particular, the information about the brake pressure in callipers is required in the ABS mode. During the ABS operation, the desired pressure in each calliper is achieved by energizing the individual proportional inlet and two-way outlet valves.

The tyre pressure control system (TPCS) allows dynamic change (both inflation and deflation) of the tyre pressure during the vehicle motion. It differentiates the proposed system from conventional tyre pressure management systems, which carry out only tyre pressure monitoring, and from automatic tyre inflation systems, which are mainly implemented on heavy vehicles and can inflate the tyres on the standing vehicle. The TPCS can change the pressure individually on each tyre. For this purpose, the system is equipped with four tyre pressure sensors p_t, inlet/outlet valves, and the air compressor. Pressure reservoirs can be also installed as option to reduce requirements to the compressor power. *The tyre pressure controller* initiates the pressure increase or decrease depending on actual maneuver conditions. For instance, the TPCS can be triggered with (i) the brake control to adjust the pressure in accordance with the surface adhesion and (ii) the suspension control to change the pressure in accordance with the surface roughness. Hence, the TPCS has preferably an integrated operation with other active chassis systems. In the presented study the 235/55 R19" tyres are being considered.

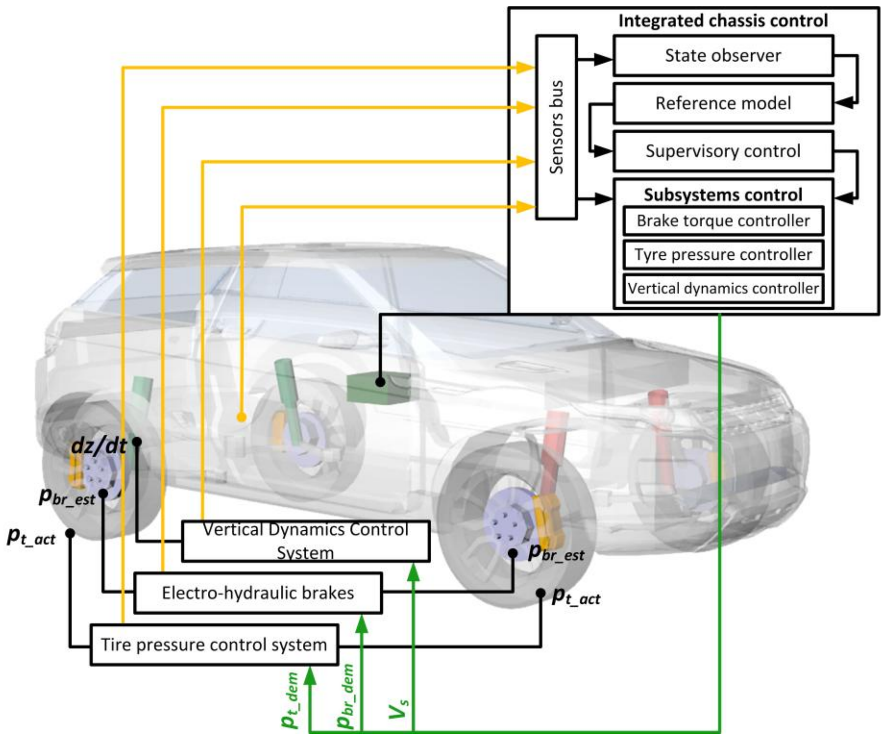


Fig. 5. *ICC architecture for the SUV demonstrator.*

The vertical dynamics control system (VeDCS) is a modification of the active suspension control and is limited, within the framework of the presented concept, by the actuation on the rear axle of the vehicle. The VeDCS is equipped with sensors measuring the vertical accelerations ($\ddot{z}$ = *dz/dt/dt*) and actuators adapting the vertical forces F_z on rear wheels to actual operation conditions through control of the voltage V_s. The VeDCS logic is defined by *the vertical dynamics controller*. The actuation dynamics is defined both by actual surface conditions (roughness, pavement characteristics) and the vehicle maneuver.

In addition to already mentioned brake, tyre pressure and vertical dynamics controllers, the global controller of the ICC includes the reference model of the vehicle, state observers and control allocation responsible for the integration of the brake control, TPCS and VeDCS. Analysis of control effects overlap and possible enhancements in vehicle safety and ride comfort is given in the next section.

4. Feasibility study

For the presented vehicle configuration, the uncoordinated control of different subsystems can have an overlapping effect and can cause unpredictable results as a consequence. Some recent studies indicate these effects showing clear influence of each particular subsystem both on longitudinal and vertical vehicle characteristics. To confirm this thesis, the target vehicle has been subjected to a real-time simulation programme using IPG CarMaker software with MATLAB/Simulink implementation of the subsystems. The vehicle was parameterized according to existing documentation and has overall mass of 2045 kg.

Each considered chassis subsystem is analyzed below for the case of their isolated operation in off-road conditions. The performance is assessed using braking performance and ride comfort criteria. Special attention is given to potential benefits from the use of ICC.

The first active chassis subsystem investigated is the *suspension characteristic variation*. As mentioned before, some experimental studies confirm the influence of the suspension configuration not only on the ride comfort but also on the braking performance [23, 24] in off-road conditions. To prove this statement for the investigated vehicle and road conditions, suspension characteristics were varied and represented by high (DH) and low (DL) damping, and high (SH) and low (SL) stiffness. All possible variations were considered and applied to the front (F) and rear (R) suspension, Fig.6-8. It is important to note that ABS was deactivated in these tests to describe effects related only to the suspension system. The initial velocity of the vehicle in all tests is 60 km/h. The maneuvers correspond to an emergency braking situation (full and fast actuation of the brake pedal by the driver).

As it can be seen on the smooth road surface, the effect during the straight-line braking maneuver is small, Fig.6. It can happen due to more flat profile as compared with Belgian paving and a surface with angled corrugations, which are considered further.

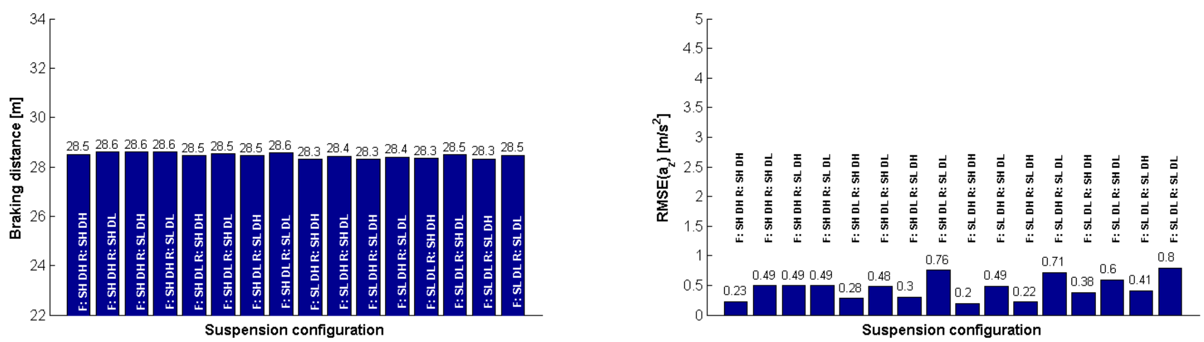


Fig. 6. *Influence of the suspension configuration on the ride comfort and braking performance on the smooth road. F – front axle; R – rear axle; SH – high stiffness; SL – low stiffness; DH – high damping; DL – low damping*

In the case of a rough surface, such as Belgian paving, Fig.7, braking distance can be reduced up to 9% by the pure variation of the suspension properties. In this case simultaneous reduction by 35% of the he root mean square error (RMSE) of the vertical vehicle body acceleration a_z can be achieved. Nevertheless, some of the particular cases are also characterized by the ride comfort deterioration. In presence of such trade-off between the comfort and vehicle safety, a decision on the target suspension characteristics should be done by the supervisory controller, Fig.5, depending on actual driving situation.

Comparing with Belgian paving a similar effect was achieved on the surface with angled corrugation, Fig.8. For the particular case the braking distance can be reduced up to 9%. The RMSE of the vertical acceleration a_z varies in the range of 65%. It is important to admit, that some simultaneous improvement in braking performance and ride comfort can be achieved.

The introduced investigation on suspension characteristics variation stresses the importance of criteria prioritization according to the driving situation and decision making in the supervisory controller. A certain improvement of the vehicle motion performance in terms of the longitudinal and vertical dynamics can be brought by the use of the active tyre pressure control system. Influence of the tyre pressure on corresponding vehicle dynamics is discussed below.

The second active chassis subsystem investigated is *tyre pressure variation.* Influence of tyre pressure variation on the braking performance is introduced in relevant studies, carried out by the authors in [25] for the same tyre type as installed on the presented vehicle prototype, namely 235/55 R19". The tests were performed on a continuously wetted surface composed of the basalt tiles, Fig. 9. It was experimentally confirmed that such typical tyre characteristics as longitudinal stiffness and peak value are being changed in accordance with the tyre pressure. For instance, the stopping distance reduction can be achieved with the reduction of the tyre pressure from 3,5 to 1,5 bar. It is caused by significant increase of the peak value of the longitudinal coefficient of friction from 0,29 to 0,38 that shortens the stopping distance up to 15% in accordance with [25]. Some similar effects were observed in [26-28] that allowed to propose a set of correction factors for the MF-Swift tyre model.

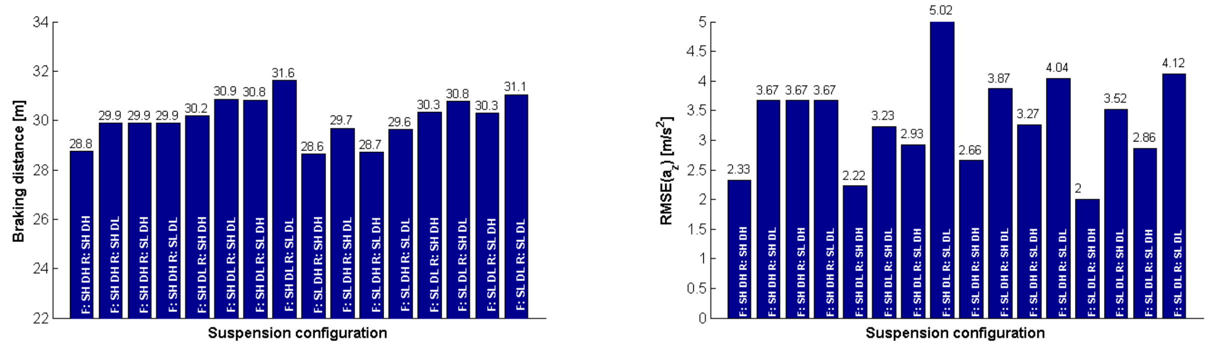


Fig. 7. *Influence of the suspension configuration on the ride comfort and braking performance on the Belgian paving. F – front axle; R – rear axle; SH – high stiffness; SL – low stiffness; DH – high damping; DL – low damping*

Angled Corrugations

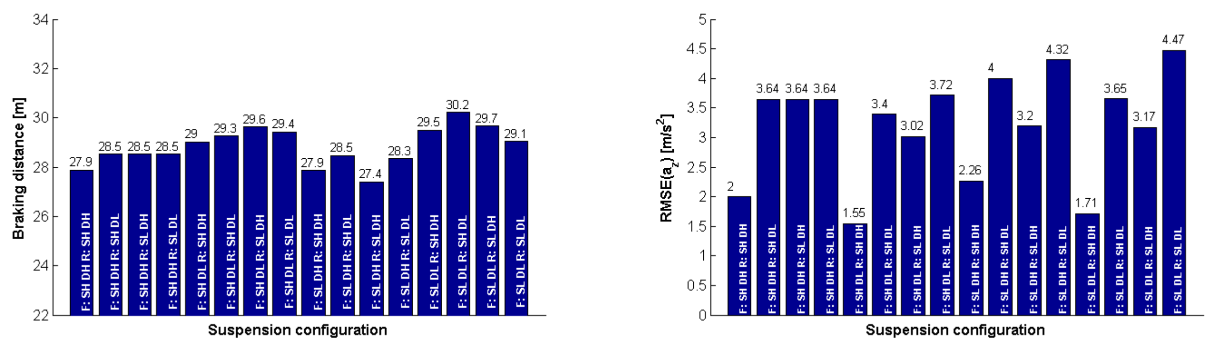


Fig. 8. *Influence of the suspension configuration on the ride comfort and braking performance on the surface with angled corrugations.*
F – front axle; R – rear axle; SH – high stiffness; SL – low stiffness; DH – high damping; DL – low damping

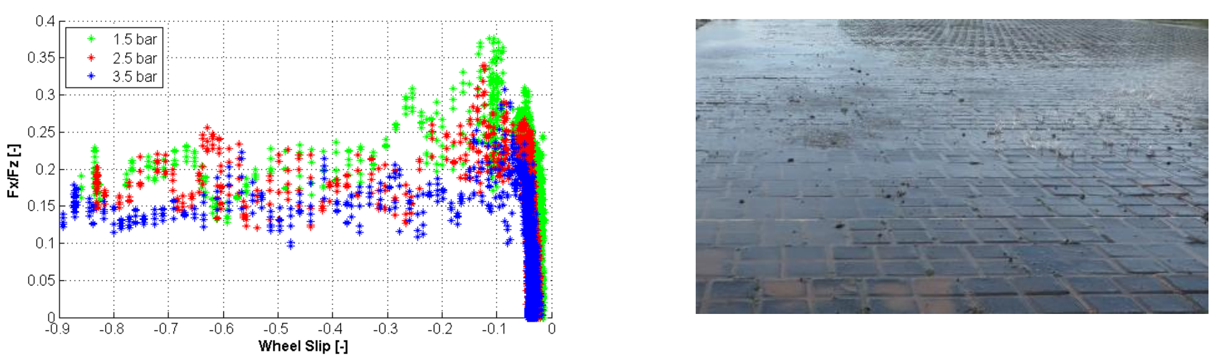


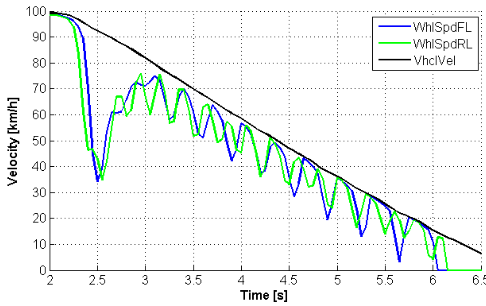
Fig. 9. *Tyre pressure inflation influence on friction-slip characteristics of wet basalt [25].*

The tyre pressure influence can be confirmed not only for the braking performance but also for the ride comfort. For example, an increase in the vertical stiffness on 35% was observed for tyre pressure variation from 1,2 to 2,3 bar for the tires 205/65 R15 [29].

For emergency situations, such characteristics as ride and driving comfort are usually not considered in the control algorithms. Nevertheless, it will be further shown how the ABS tuning parameters can also dramatically influence the ride and driving comfort.

The third active chassis subsystem investigated is the *braking system*. The proposed ABS algorithm was specifically developed for the introduced ground vehicle and is characterized by the dependence of the ride and driving comfort characteristics from the ABS operational frequency. Typical ABS diagrams can be seen on Fig. 10 illustrating the braking with low (configuration 1) and high (configuration 2) operational frequency. Both configurations have similar results in terms of the average deceleration (-5,67 and -5,49 m/s^2 respectively), thus a pure influence on the vertical body acceleration and longitudinal jerk can be assessed. The baseline case corresponds to the vehicle with deactivated ABS. This case has no force fluctuations due to the ABS operation and, therefore, a priori better characteristics of the ride and driving comfort. However, the baseline vehicle has then a worse braking performance with longer stopping distance.

a)



b)

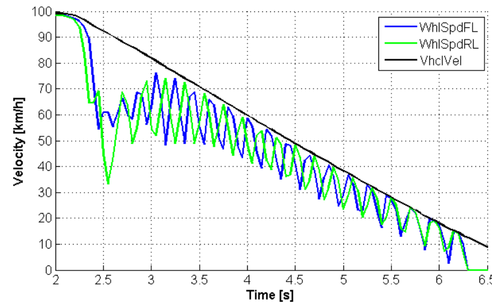
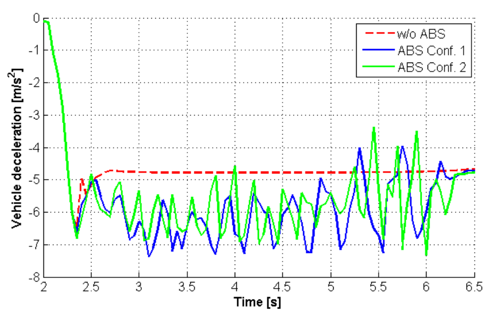


Fig. 10. *Inflation of the ABS operational frequency on the vertical vehicle body acceleration.*
a) Configuration 1; b) configuration 2.

The next important observation is that the ABS tuning can play a crucial role in the ride comfort during the emergency braking situations, Fig. 11. As compared to the baseline vehicle without ABS, configuration 1 provides, on the smooth road, a 34%-increase of RMSE(a_z) and a 56%-increase of RMSE(j_x), whilst configuration 2 has higher values: an increase of 55% and 316% respectively. These results are summarized in Table 1 and show how strong the influence of the ABS can be on the ride comfort even on the smooth road.

a)



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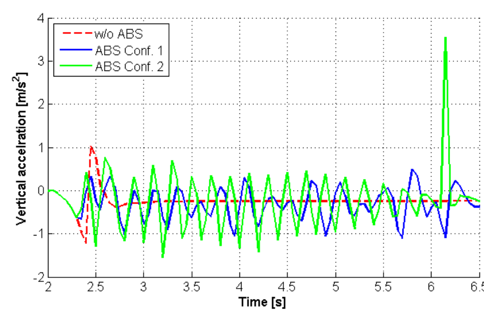

c)

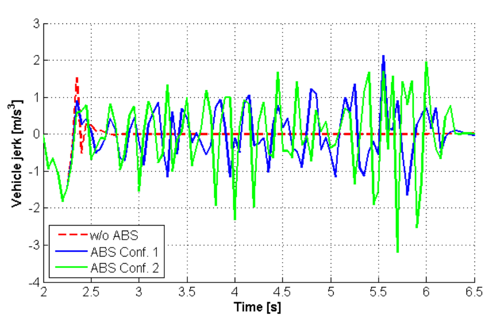

Fig. 11. *Inflation of the ABS operational frequency on the vertical vehicle body acceleration and longitudinal jerk.*
a) Vehicle deceleration; b) vertical vehicle acceleration; c) vehicle jerk.

Table 1. Real-time simulation results with ABS tuning parameters variation.

ABS Configuration	*Mean longitudinal acceleration (a_x)*	*RMSE vertical acceleration (a_z)*	*RMSE longitudinal jerk (j_x)*
w/o ABS	-4.45	0.31	0.31
ABS Configuration 1[a]	-5.67	0.47	0.71
ABS Configuration 2[b]	-5.49	0.69	1.01

[a] Low operational frequency.
[b] High operational frequency.

It can be concluded that three discussed systems (brake, tyre, suspension) can play a significant role in the longitudinal and vertical dynamics control simultaneously. Taking this fact into account, a solution of the ICC is proposed in the next section.

5. Subsystems integration

Within the framework of the presented paper, a detailed description of the developed integrated controller and corresponding subsystem controllers is not given due to the manuscript limitations. However, to illustrate the subsystem integration, the straight-line braking case is being discussed, where the initial vehicle velocity is 100 km/h. In the real-time simulation some assumptions were made. In particular, variation of the tyre vertical stiffness due to the pressure changes is neglected due to the lack of experimental investigation on the current stage of the project. Three types of the road surface are considered: (i) smooth road; (ii) Belgian paving, and (iii) surface with angled corrugations.

To show evolution of the system performance, several vehicle configurations are investigated: (i) baseline SUV without any of active subsystems and ABS; (ii) target vehicle with only ABS activated; (iii) **ICC_1** with ABS and TPCS on the board; (iv) **ICC_2** with ABS and VeDCS; (v) **ICC_3** with integration of ABS, TPCS and VeDCS. For all ICC configurations, the global goal is firstly aimed at the achievement of better braking performance, whilst ride and driving comfort is of secondary priority.

The braking performance is numerically described by the braking distance value, and the ride comfort is characterized by the RMSE value of a_z. Of secondary importance in terms of control priority is the driving comfort that has RMSE of j_x as a numerical indicator.

To show the operation of the most complicated ICC configuration, the emergency braking on the smooth road was performed and corresponding data are shown on Fig. 12. As it can be seen, the functionality of the ABS is not deteriorated first of all, and the vehicle achieves maximum possible deceleration on the corresponding surface, Fig.12(a). Moreover, some additional contribution is done by the TPCS by reducing the pressure from 2,5 to 0,5 bar, Fig. 12(d). Such reduction visibly increases the peak value of the coefficient of friction between the tyre and road, Fig.12(c). The cycles performed by the ABS system, Fig.12(a), can produce some negative influence on the ride comfort properties as it was mentioned in the previous section. To improve the ride comfort under the influence of ABS and to reduce the vehicle pitching due to the emergency braking, VeDCS generates forces on the rear axle, Fig.12(f), and reduces the vertical acceleration of the vehicle body as it is shown on Fig.12(e).

Results for the other vehicle configurations and their comparison are summarized in Table 2. As it can be seen on the smooth road compared to the baseline vehicle, all the configurations have achieved better results in terms of the braking performance. It is important to admit that some small distance reduction and significant ride comfort improvement was achieved by the use of integrated ABS and VeDCS compared to the pure ABS application. It shows some positive effect of the VeDCS not only in its direct task of the vertical acceleration reduction but also in the stopping distance reduction. Hence, VeDCS supports the ABS system functionality. As it can be seen in the case of ICC_1, engagement of the TPCS deteriorates the ride comfort but shows simultaneously the stopping distance reduction. Comparing with ICC_1, ICC_2 shows the best result in terms of the braking performance and some descent results in terms of the ride comfort.

An additional advantage from the VeDCS application can be seen in the case of Belgian paving and surface with angled corrugation, where the vehicle body acceleration is much higher due to the road roughness or wheels can lose contact with the road. As a result, ICC_3 shows the best results in terms of the braking performance and ride comfort on the both surfaces.

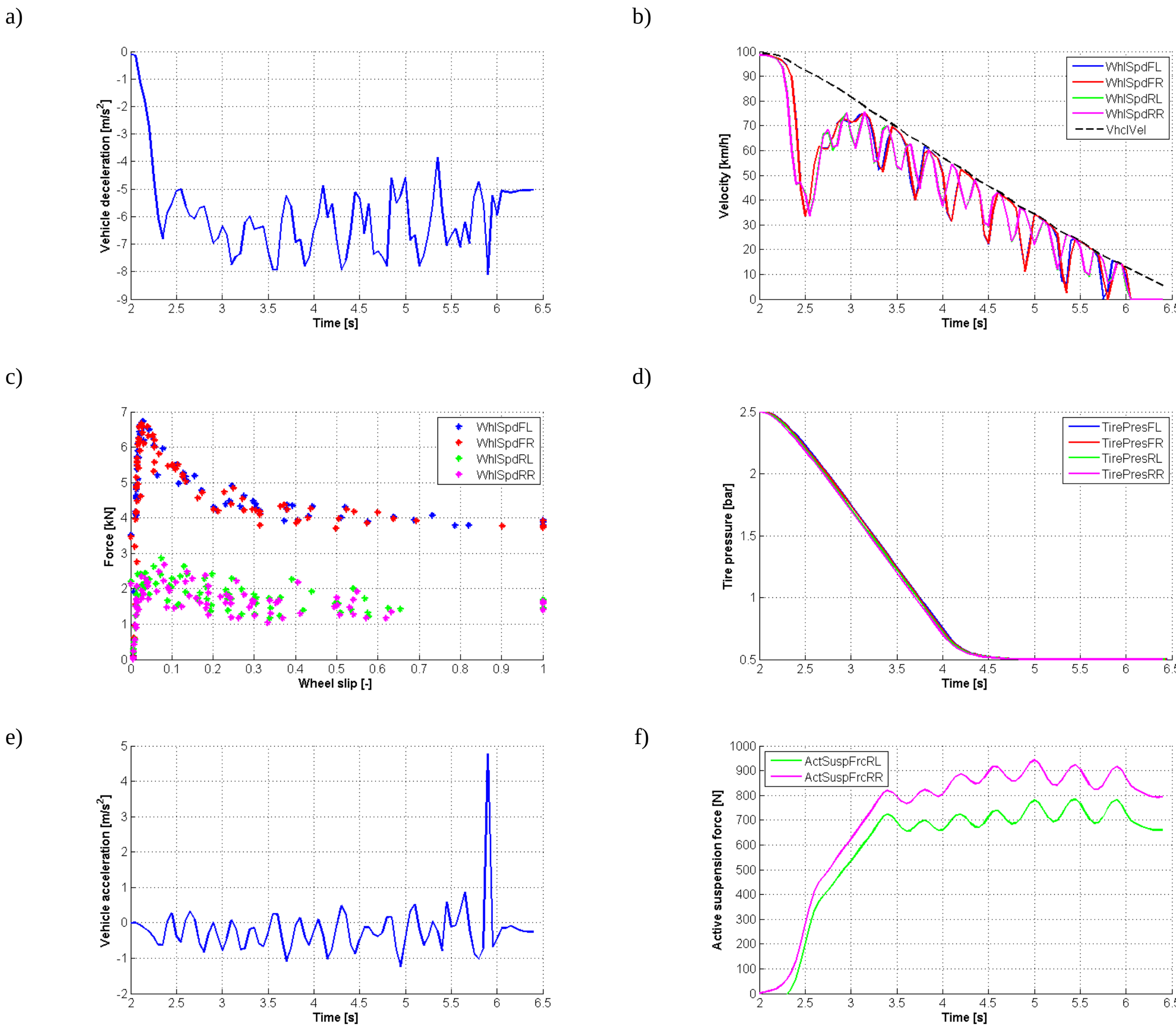

Fig. 12. *ICC operation during the emergency braking on smooth road.*
a) Vehicle deceleration; b) vehicle and wheels speeds; c) tire forces; d) tire pressure inflation; e) vehicle body vertical acceleration; f) VeDCS actuators forces.

Table 2. Real-time simulation results.

Test	**Criteria**	**Baseline vehicle**[a]	**Stand-alone ABS**	**ICC$_1$ (ABS,TPCS)**	**ICC$_2$ (ABS,VeDCS)**	**ICC$_3$ (ABS, TPCS, VeDCS)**
Smooth road	Braking distance, m	79.3	66.9	65.1	66.6	64.9
	$RMSE(a_z)$	0.32	0.47	0.65	0.36	0.59
	$RMSE(j_x)$	0.33	0.91	0.89	0.88	0.90
Belgian paving	Braking distance, m	75.9 [b]	78.9	75.5	71.3	68.6
	$RMSE(a_z)$	4.43 [b]	5.49	5.09	4.28	4.40
	$RMSE(j_x)$	4.57 [b]	5.79	6.3	5.63	6.16
Angled corrugations	Braking distance, m	75.5	74.1	73.8	74.3	73.2
	$RMSE(a_z)$	2.97	3.84	4.62	3.46	3.36
	$RMSE(j_x)$	2.80	4.87	5.17	4.16	4.44

[a] Vehicle with deactivated ABS, TPCS and VeDCS.
[b] Vehicle has lost the trajectory.

6. Conclusions and future investigations

Considering the results introduced in previous sections, this study has following outcomes:

- Literature survey of the existing ICC solutions was done;
- Rarely explored problematic of subsystems integration during the longitudinal vehicle motion was taken into account;
- Feasibility study was performed for suspension, tyre and brake system explaining trade-off between braking performance and ride comfort and showing significant potential for the system integration
- The proposed ICC variant shows promising results compared to other vehicle configurations in off-road conditions.

For further studies, the following tasks can be formulated:

- Influence of the tyre pressure variation on the vertical tyre stiffness will be considered and validated on the experimental level;
- Energy consumption of each actuator and overall energy characteristics will be considered in the ICC;
- Due to the lack of controllers tuning in current version, further significant improvement of vehicle motion performance in off-road conditions is foreseen by application of optimization procedures;
- Control algorithm will be implemented on the real demonstrator equipped with corresponding active systems.

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