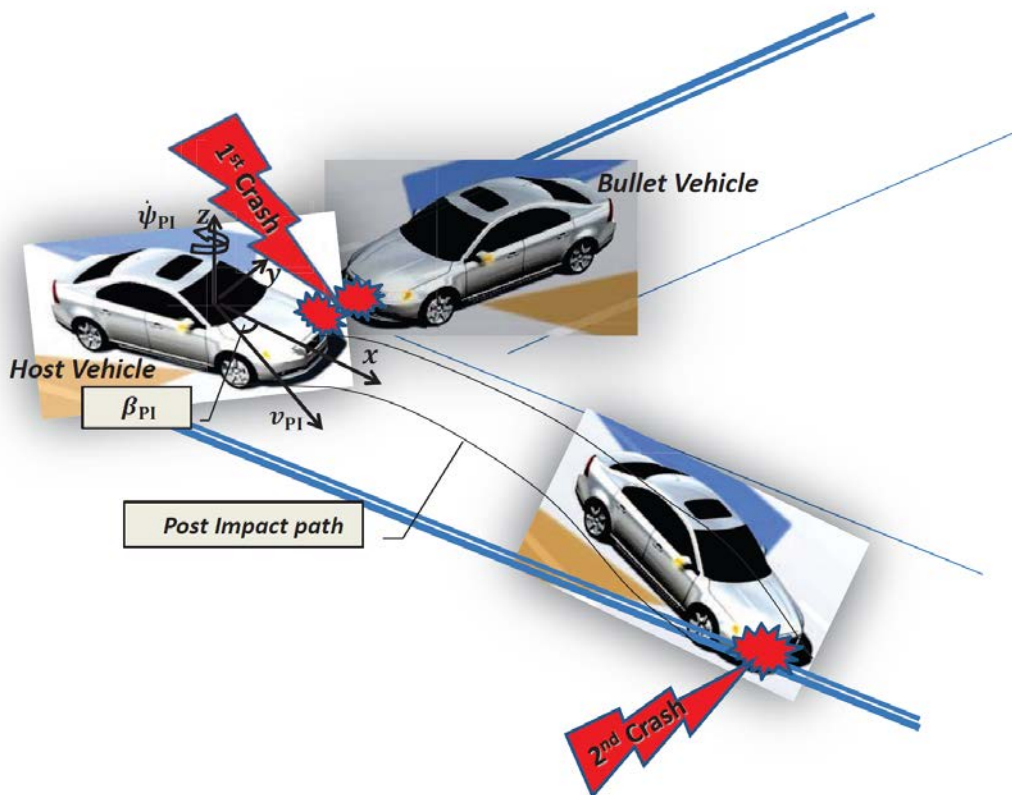


Post Impact Stability Control (PISC)

VINNOVA Reference number: 2011-03631



Project within FFI - Vehicle and Traffic Safety

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Date: 2014-04-17



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Executive summary

Accidents statistics show that multiple-event accidents (MEAs) represent a considerable and increasing proportion of all vehicle traffic accidents. MEAs are characterized by having at least one vehicle subjected to more than one harmful event. MEAs now comprise approximately 25% of all passenger vehicle accidents. This thesis aims to make systematic progress towards developing a vehicle Post Impact Control (PIC) function so as to avoid or mitigate any secondary event in MEAs.

To characterize the vehicle motion control problems for PIC, a number of MEAs from an accident database were analysed. Post impact vehicle dynamics were studied considering the overall accident scenarios of exemplar cases. Reduction of kinetic energy and path lateral deviation were found to be most critical and beneficial for the vehicles after impacts.

To understand the mechanism of influencing the post impact vehicle path, numerical optimization was applied to minimize the maximum path lateral deviation. It was found that effective control can be achieved across a wide range of kinematic conditions, by switching between three substrategies established at vehicle body level. Results also showed that active front-axle steering, in addition to individual-wheel braking, provides significant control benefits, although not for all post-impact kinematics.

For closed-loop design of the path control, a Quasi-Linear Optimal Controller (QLOC) was proposed and verified with the numerical optimization results. The design method is novel; it well combines the linear co-states dynamics and nonlinear constraints due to tyre friction limits. The algorithm was further adapted to penalize both longitudinal and lateral path deviations, using a generalized cost function.

To verify the function with driver interaction, a number of exploratory methods were investigated regarding the driver safety, as well as the capability and accuracy to reproduce the real-world post-impact vehicle kinematics. A scheme of the function design for real-time implementation was proposed and applied to the experiments in a driving simulator environment.

Keywords: Vehicle Dynamics, Optimization, Path Control, Post Impact, Collision Avoidance, Multiple-Event Accidents, Accident Analysis.



1. Background

Vehicle traffic safety has been attracting considerable attention from all perspectives, given the continuing high numbers of accidents registered in road traffic statistics. One type of accident is gradually increasing according to the recent accident statistics: multiple-event accidents (MEAs). These are characterized by having at least one vehicle subjected to more than one harmful event, such as collision with another vehicle or object. Statistics show that MEAs comprise approximately 25% of all passenger vehicle accidents; in particular, two-impact accidents account for about 70% of all planar MEAs which have no roll-over; and human injury levels in MEAs are higher than in single-event accidents (SEAs), with more than one third of accidents with severe (i.e. AIS3+) injuries being MEAs. Studies on more recent accident statistics show that MEAs have a threefold risk for severe and four-fold risk for fatal injury compared to SEAs; on average, 50% of all passenger vehicles suffering MEAs have the severe injuries sustained in one or several subsequent impacts. The research motivation is hereby the following real-world problem: Vehicles and human beings are subjected to more than one hazardous event in the traffic accidents.

2. Objective

The concerns arising around vehicle and traffic safety, actively incorporate relevant research in academia while also propelling safety systems development in the automotive industry. Nowadays, vehicle safety systems are widely categorized as preventive systems which aim to prevent the imminent crashes; and protective systems which protect the human beings by reducing injuries. In the recent decades, various vehicle dynamics control functions have been widely industrialized as active safety systems on-board that have substantially contributed to the reduction of injuries and damage in traffic accidents. The most relevant one connected to the MEAs problem described above is the Electronic Stability Control (ESC) system; this functionality is being continuously improved by several added-valued features, e.g. rear-axle side-slip control, roll-over mitigation, trailer sway control etc. Although there exist numerous names and versions of ESC algorithms on the market, the fundamental principle is mostly the same: deduce and follow the driver's intended yaw rate within the limits of various stability criteria, by active braking and steering which re-distributes the tyre longitudinal and lateral forces, so as to improve vehicle handling performance near the limit of tyre-road adhesion. On-track tests and accident statistics show that ESC can effectively stabilize the vehicle yaw instability due to external disturbances of low amplitudes, e.g. aggressive driver manoeuvres, side-winds and uneven tyre friction. A general figure of ESC effectiveness summarized from the accident studies by Linder et al. is around 20-50%, which largely depends on vehicle type, injury severity level, type of accident, road conditions etc. Considering the most ESC-pertinent types of accidents, it was estimated that about 35% less risk is expected for cars getting into serious accidents when equipped with ESC, compared with the ones



without ESC. A literature review by Ferguson came to the conclusion that in the USA, fatal single-vehicle crashes involving cars are reduced by about 30-50% and SUV by 50-70%. Fatal rollover crashes are estimated to be about 70-90% lower with ESC regardless of vehicle type. There is little or no effect of ESC in all multi-vehicle crashes. Generally, ESC effectiveness is seen as improved when the road condition is slippery. However, there is no evidence indicating that current ESC systems can handle relatively high amplitudes of disturbances, such as an impact, onto the car body. Firstly, during the impact, the sensors signals could be implausible due to high accelerations and velocities, in which case ESC could be deactivated. Secondly, after the impact, the vehicle is exposed to violent spinning and skidding motions which are likely to be beyond the efficient operation range designed by current ESC algorithms. In most cases, even if the stabilization can eventually be achieved, it takes too much time and space so that the probability of a secondary event is hardly lowered. Thirdly, the main reference of ESC interventions is derived from the driver, who is possibly unable to act correctly to accomplish a successful avoidance manoeuvre during and after the impact¹. The research question that appears is: How to control the post impact vehicle motion in order to avoid or mitigate the secondary events in multiple-event accidents?

3. Project realization

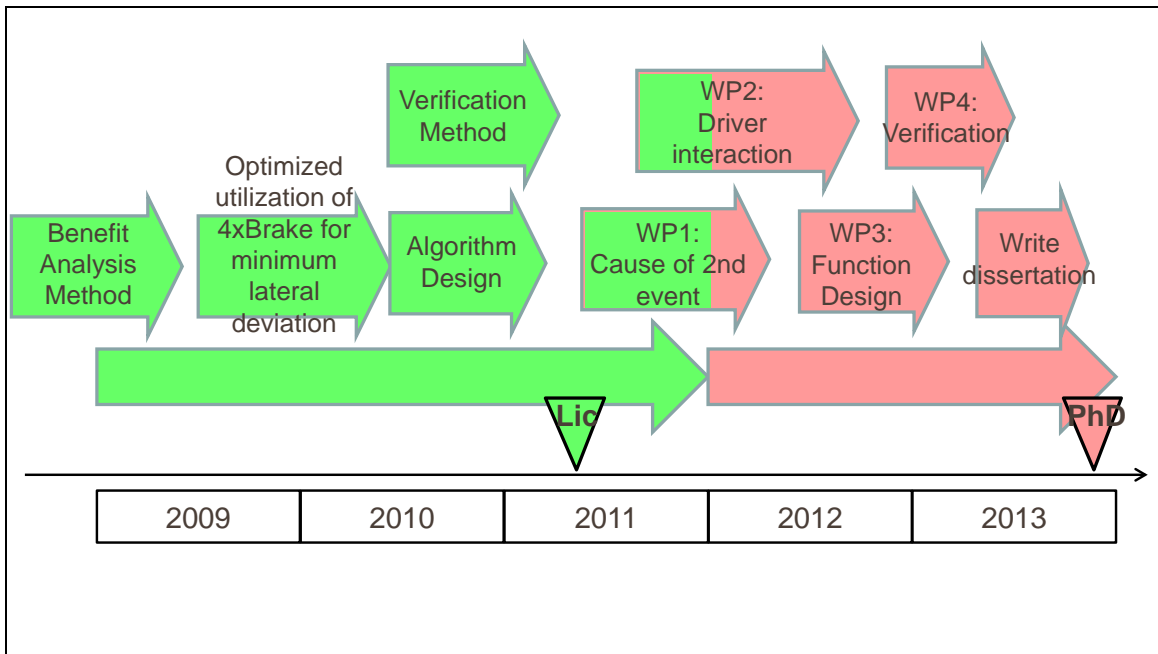


Figure 1 Time plan. Green = 1st part. Red= 2nd part. The report concerns the 2nd part, 2012-2013.

WP1: Cause of 2nd event

This part was basically to further develop the cost function to include other control objectives than minimizing the lateral displacement solely. Reducing vehicle speed and controlling yaw angle are central here. It was considered whether PISC function can be completely blind, or if information from environment (e.g. forward looking camera) is needed.

Research Question: "How shall different control objectives be optimally tackled to minimize the risk of injuries in MEAs?"

WP2: Driver interaction

So far, the available actuators have been individually controlled brakes, and absence of driver action has been assumed (zero brake pedal and zero steering wheel angle). Now, it was suggested to also add a steering system, such as EPAS. This is because front axle steering (by electrical steering assist, EPAS) is likely to be an available actuator of almost all passenger vehicles in a close future. Alignment steering wheel torque was also investigated. Steering clearly adds in the question about driver interactions, since it has two way communication with driver, steering wheel angle and torque. Similar issues appear with brake pedal. There are different alternatives, on a top level: let driver action



cancel the PISC function, add driver action and PISC function requests or neglect driver actions.

Research Question: "How should a PISC function best interact with a driver?"

WP3: Function design

A function was designed. It concentrated on the algorithms needed for controlling the actuators which are found to have the best potential, i.e. brake and/or front axle steering. The function had to handle driver interactions. It assumed realistic sensor/estimation information, but the algorithms needed for detection, plausibility and characterization of the 1st impact does not have to be included.

VCC contributed by involving Passive Safety department and/or airbag supplier to define state of the art detection, plausibility and characterization of the 1st impact. Actual data logs from vehicle crashes in VCC crash lab was useful. VCC also deepened the requirement on sensor signals, especially 1st impact detection, plausibility and characterization.

VCC contributed with deciding which the reference case should be, i.e. does the reference vehicle have an active ESC or not and does the reference vehicle have a Post Impact Braking function or not.

Research Question: "How could a PISC function be designed, taking all earlier knowledge gained in project, into account?"

WP4: Verification of PISC strategies

Particularly important is the driver's experience and the understanding of when a PISC function should be deactivated (driver override). Some simplifications and assumptions that have been made under the work should be evaluated to verify (if they were appropriate). Verification on research level was made. To some extent in real vehicle on test track, but mainly in simulator. It also provided valuable knowledge how a driver reacts when the vehicle is autonomously controlled after a crash.

Research Question: "How will driver react on the proposed PISC function? How will the PISC function itself work in a more realistic scenario than pure simulation?"

4. Results and deliverables

Project goal

The project had the aim to contribute to solutions that reduces injuries/occurrence of multiple-event accidents. 1/4 of all accidents are multiple-event accidents. The expected



result is a function definition of Post Impact Stability Control and knowledge how to take it further. This aim has persisted throughout the project.

Achieved results

The overall result is a function definition of Post Impact Stability Control and knowledge how to take it further. This function will result in significantly avoided or mitigate multiple event accidents.

Project effects

The project has contributed with scientific findings in the field of path control, driver behaviour and injury analysis. Cooperation with University of Michigan has been established. The PhD student has been employed by Volvo Cars.

14 papers, 3-4 MSc theses, 1 patent applications, 1 PhD graduated

Delivery to FFI-goals

The goal of the project addresses the following overall programme goals:

The overall target will contribute to traffic safety.

Selected FFI programme targets which are especially relevant for the proposed project:

- contribute towards a vehicle industry in Sweden that continues to be competitive
- lead to industrial technology and competence development
- support environments for innovation and collaboration
- strive to secure national supplies of competence and to establish R&D with competitive strength on an international level

5. Dissemination and publications

6.1 Knowledge and results dissemination

Some car manufacturers have, during project, launched post impact braking, which is a simpler version of post impact stability control. This shows an increased interest of this type of active safety functions.

6.2 Publications from the project

1. [Minimizing Vehicle Post Impact Path Lateral Deviation Using Optimized Braking and Steering Sequences](#), Yang, Derong; Jacobson, Bengt; Jonasson, Mats; Gordon, Timothy, Scientific journal article - peer reviewed, 2014
2. [Prediction of the Effectiveness Potential of a Post Impact Stability Control System for Passenger Cars in Secondary Collisions following an Initial Side Impact](#), Jacobson, Bengt; Yang, Derong; Thor, Mikael; Lu, Jianbo; Lidberg, Mathias, Conference paper - non peer reviewed, 2014
3. [An Optimal Path Controller Minimizing Longitudinal and Lateral Deviations after Light Collisions](#), Yang, Derong; Gordon, Timothy; Jacobson, Bengt; Jonasson, Mats, Conference paper - peer reviewed, 2013
4. [Vehicle tyre to road friction value estimation arrangement](#), Jonasson, Mats; Jacobson, Bengt; Yang, Derong; Gordon, Timothy, Patent application, 2013
5. [Towards Evaluation of Post Impact Braking Function in Driving Simulator](#), Al Mouatamid, Faouzi; Kusachov, Artem; Jacobson, Bengt; Yang, Derong, Conference paper - peer reviewed, 2013
6. [Closed-loop Controller for Post Impact Vehicle Dynamics Using Individual Wheel Braking and Front Axle Steering](#), Yang, Derong; Jonasson, Mats; Jacobson, Bengt; Gordon, Timothy, Scientific journal article - peer reviewed, 2013
7. [Vehicle Dynamics Control after Impacts in Multiple-Event Accidents](#), Yang, Derong, Doctoral thesis, 2013
8. [Quasi-linear Optimal Path Controller Applied to Post-Impact Vehicle Dynamics](#), Yang, Derong; Gordon, Tim; Jacobson, Bengt; Jonasson, Mats, Scientific journal article - peer reviewed, 2012
9. [Closed-loop Controller for Post-Impact Vehicle Dynamics Using Individual Wheel Braking and Front Axle Steering](#), Yang, Derong; Jonasson, Mats; Jacobson, Bengt; Gordon, Tim, Conference paper - peer reviewed, 2012
10. [A nonlinear post impact path controller based on optimised brake sequences](#), Yang, Derong; Gordon, T. J.; Jacobson, Bengt; Jonasson, M., Scientific journal article - peer reviewed, 2012
11. [Optimized brake-based control of path lateral deviation for mitigation of secondary collisions](#), Yang, Derong; Gordon, T. J.; Jacobson, Bengt; Jonasson, M.; Lidberg, Mathias, Scientific journal article - peer reviewed, 2011
12. [Post Impact Vehicle Path Control in Multiple Event Accidents](#), Yang, Derong Licentiate thesis, 2011

13. [Post-Impact Vehicle Path Control by Optimization of Individual Wheel Braking Sequences](#), Yang, Derong; Gordon, Timothy; Lidberg, Mathias; Jonasson, Mats; Jacobson, Bengt, Conference paper - non peer reviewed, 2010
14. [Benefit Prediction of Passenger Car Post Impact Stability Control Based on Accident Statistics and Vehicle Dynamics Simulations](#), Yang, Derong; Jacobson, Bengt; Lidberg, Mathias, Conference paper - non peer reviewed, 2009

6. Conclusions and future research

Conclusion

This research aims to make systematic progress towards solving a real-world traffic safety problem that has been threatening human lives: multiple-event accidents (MEAs) where the passenger vehicle is subjected to more than one event, and the severity of the entire accident is intensified by the subsequent events. The envisioned solution is to actively control the vehicle motions after a primary collision in MEAs, as a critical complement to any on-board injury prevention systems.

To provide a solid foundation in understanding the underlying causes of secondary collisions in MEAs, accident data were first studied so that the vehicle directional control problems after impacts were characterized, in terms of both the vehicle dynamics states and the accident scenarios. To resolve one dominating symptom of the problem, i.e. excessive path lateral deviation, the trajectory optimization techniques were adopted to identify the optimal path control strategy which was found to be distinctive compared to the conventional stability control functions. Thereafter, a closed-loop quasi-linear optimal path controller was proposed to provide an approximation to the optimal strategy found in open-loop numerical optimizations. The resultant balanced control between global lateral force and yaw moment was further allocated to the optimal individual wheel brake torque and front axle steer angle requests.

In real-world road traffic, the safe area for vehicle travelling can evolve continuously in time. Hence, an on-line estimation of the direction of maximum crash risk is important in order to effectively avoid or mitigate the subsequent events in real-time. In this thesis, a general form of the cost function was proposed to consider the expected crash risk and severity, which can be estimated with the sensor signals in the vehicle and infrastructure. An example of this cost formulation was applied in the optimal path controller which limits both the longitudinal and lateral deviations from the point of initial impact.

Considering the uncertainties in driver and vehicle states estimation as well as in environment sensing, it can be demanding to achieve the exact solution of the optimal vehicle motion control after impacts. Nevertheless, the work in this thesis has shown that significant improvement in vehicle traffic safety can be achieved if the optimal control strategy can be realized using the available actuators on-board. Results from the simulations and the ongoing experiments in driving simulators suggest that, the safety



benefits gained from optimal tyre force re-distribution can not be underestimated for the avoidance or mitigation of secondary events in multiple-event accidents.

Future work

The complexity of addressing this collision mitigation problem in a postimpact scenario is not insignificant. The following issues are considered most critical for improving the design of the proposed post impact control function, especially from the optimal path control point of view:

- **Seamless interface with driver** A number of driver overriding criteria were applied in the driving simulator tests for PIC function verification; these were mostly focused on brake torque superimposition. It is expected that more research can be done to evaluate the human machine interface between the function and driver requests. For instance, using the EPAS system, an abrupt steering torque input superimposed onto the steering wheel may possibly injure the driver's hands. Hence, it may be necessary to limit the rotational torque applied to the steering wheel, even if this can degrade the controller performance. It is also critical to determine the timing and actions associated with returning control back to the driver, especially to avoid misunderstandings between the vehicle controller and human driver. Inclusion of the steering actuator may also increase the risk of vehicle motion overshooting after the point of maximum lateral displacement being reached, which may impose a more challenging task for the settling phase. It is expected that in future work, the settling controller should be improved in order to better track a desired profile of vehicle speeds in road coordinates.
- **Verification in experimental vehicles** An important contribution to the further development of PIC function will be to test and validate the control algorithm, especially the actuators' capability, through implementation on experimental vehicles. This is in addition to the aim of verifying driver-machine interaction in a driving simulator; experiments in real vehicles should be able to demonstrate the controller performance either without a driver in the control loop, or with a virtual "post impact driver" model deduced from the studies using driving simulators.
- **Control arbitration for high CG vehicle** For a high CG vehicle, e.g. SUV and light trucks, the roll and lateral acceleration immediately after the initial impact can be so large that path control alone may not be able to mitigate an un-tripped roll-over as the secondary event. Control arbitration needs to be determined in order to best manage the brake and steer requests between PIC function and a separate controller such as Roll Stability Control (RSC) function.
- **Scenario identification and multi-objective criteria** In this thesis, a general form of real-time crash risk and injury cost function was proposed. One particular topic for future research is in the area of further evaluation and parameterization of such a cost function. Depending on the amount of information available about the environment, the field of safe travel can be sketched so that a hierarchy of targets for risk reduction can be developed in



real-time. For instance, if curved road boundaries are identified from on-line digital maps, path deviation perpendicular to the road boundary at the predicted maximum off-tracking point would be avoided as a priority. Or if collision becomes unavoidable, the priority should switch to crash mitigation so that crash severity is minimized; the optimal strategy depends on the detail and quality of the scenario identification and the intended control response should be based on multi-objective criteria.

In the path controller, the displacements were measured at the mass centre, while the paths of the corner points of the vehicle body are especially important for assessing collision consequence. These trajectories can be typically wrapped within an envelope which is a curve tangent to each path at some point, and bounds their combined maximum path deviations. This is a relevant issue because the impending secondary collision can happen to any point of the vehicle as a rigid body in the road and off-road map. Therefore, the collision probability can depend on the vehicle yaw angle and also road layout, apart from the trajectory at CG. It is expected that the yaw angle control can become important as a top-level objective for large path lateral deviation of the mass centre since the vehicle could be exposed to the on-coming track. Sensors and actuators failures It may be that, during the initial impact, some damage is sustained to cause sensors or actuators to fail. Provided faults or partial system failures can be identified in real-time, control adaptation should be feasible. In the case of actuator faults, the constraints on Hamiltonian minimization should take this into account. In other cases, such as sensors for yaw angle estimation being lost, it could be that PIC would default to a simpler control strategy, such as full braking. Similar to the identification of the external scenario, the topic of internal system fault detection, identification and compensation is worthy of much deeper consideration in the future.

7. Participating parties and contact person

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