Benefit Prediction of Passenger Car Post Impact Stability Control Based on Accident Statistics and Vehicle Dynamics Simulations

Proceedings of 21st IAVSD Symposium on Dynamics of Vehicles on Roads and Tracks, 2009

Citation for the published paper:
Yang, D. ; Jacobson, B. ; Lidberg, M. (2009) "Benefit Prediction of Passenger Car Post Impact Stability Control Based on Accident Statistics and Vehicle Dynamics Simulations". Proceedings of 21st IAVSD Symposium on Dynamics of Vehicles on Roads and Tracks, 2009

Benefit Prediction of Passenger Car Post Impact Stability Control Based on Accident Statistics and Vehicle Dynamics Simulations

Derong Yang[a], Bengt Jacobson[b], Mathias Lidberg[a]
[a]Department of Applied Mechanics, Chalmers University of Technology, SE-41296, Göteborg, Sweden,
derong.yang@chalmers.se; [b]Vehicle Dynamics & Active Safety, Chassis Engineering, Volvo Car Corporation,
SE-40531, Göteborg, Sweden.

Abstract

Accident statistics showed that about 30% of passenger car accidents are multiple-impact events (MIE). Current Electronic Stability Control (ESC) systems are well designed for vehicle yaw motion control due to aggressive driving maneuvers, but not for that under external disturbances on the car body. A post impact stability control (PISC) system is thus envisioned to avoid or mitigate the subsequent events after the first PISC-triggering impact. In this work, a method for the benefit prediction of passenger car PISC system is formulated, based on accident statistics and vehicle dynamics simulations. The representative accident cases are selected; the problematic areas in terms of post impact vehicle dynamics are analyzed; thus the benefit measures are determined for each case, taking the accident environmental factors into account. PISC benefit is predicted by quantifications on each benefit measure, using a PISC function that selects between two controllers, i.e. Differential Braking and Lock Front Axle. Thereafter, requirements on the improvement of each benefit measure can be generated and utilized throughout the function development process, especially for the algorithm optimizations.

1. INTRODUCTION

Vehicle traffic safety has been attracting considerable attention with an increasing amount of accidents registered in road traffic statistics. One type of accident is gaining more and more attention via accident statistics studies – Multiple-Impact Events (MIE). It characterizes an accident having at least one vehicle subjected to more than one event (1st event as collision or roll-over or side-wind disturbance). Statistics shows that MIE share for light passenger vehicles is around 28% and human injury level in MIE is higher than in single-collision event and 1/3 of severe accidents are MIE type [1, 2, and 3]. One safety solution, Post Impact Stability Control (PISC), is thus envisioned to avoid or mitigate those subsequent events after the first one, by vehicle dynamics control taking both the vehicle stability parameters and environmental situation into account. In this context, Haddon's matrix [4] is extended for MIE accidents, so as to place and interpret the role of PISC considering the entire process of an accident (***Figure 1***).

HADDON's Matrix extended for MIE	Pre-accident			Accident			Post-accident
	Normal Driving	Collision Avoidance	Collision Imminent	1st Collision	Post 1st Collision	Secondary Events	
Vehicle	**ADAS:** Night vision, Alco-lock, BLIS, TPMS, ABL, DAC, ACC etc.	**ADAS:** LDW, DAC, FCW etc.	**Active Vehicle Dynamics Control:** CMbB, City Safety etc.	Robust crash detection, verification and characterization.	**Active Vehicle Dynamics Control:** ***PISC, PIB***	**Passive Safety:** Seatbelt, Airbag, IC, WHIPS, Collapsible steering column, Pedestrain Protection etc.	Event data recorder, minimized likelihood of post-impact fire on oil tank, etc.
		Active Vehicle Dynamics Control: ABS, ESC, RSC, ASR, RWS etc.	**Passive Safety:** Seatbelt pretension, Energy-absorbing structures etc.	**Passive Safety:** Seatbelt, Airbag, IC, WHIPS, Collapsible steering column, Pedestrain Protection etc.			Automatic call for ambulance etc.
Driver	Qualified driving education	Proper interaction with vehicle	Not panic, correct maneuvre	High physical tolerances to crash forces, wearing seatbelt etc.			Survivied /less injured
Environment	Clear road signs, paving condions, GPS etc.	Rumble stripes, sensors on infrastructure etc.	Rumble stripes	Guard rails and other fixed object near roadway	Qualified sensors on infrastru-ctures, road maps	Qualified sensors on infrastru-ctures, road maps	Effective emergency response, social system for victim rehabilitation

Figure 1 Haddon's Matrix in MIE accident.

External disturbances on the car body will give rise to vehicle instability due to extreme redistribution of the tire forces, which makes it difficult, if not impossible, for a driver and a current Electronic Stability Control (ESC) system to counteract. It is shown that the cars exposed to external impulse and aggressive steering inputs can display quite different state trajectories in terms of yaw rate and side slip angle development (***Figure 2***).

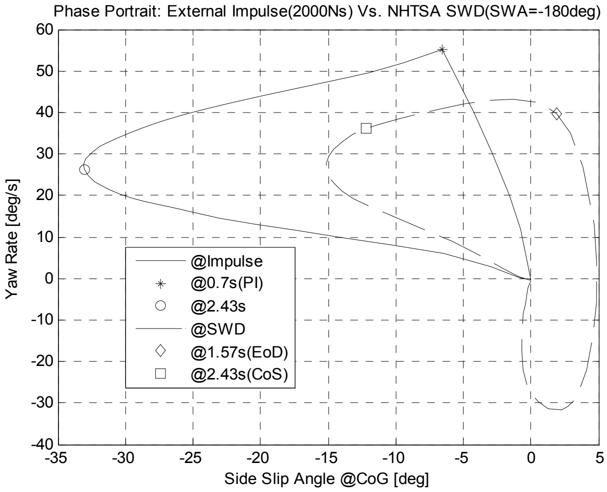


Figure 2 Phase Portrait for car exposed to external impulse (PI: post-impact) Vs. car exposed to aggressive Sine with Dwell maneuver (EoD: End of Dwell; CoS: Close of Steering), speed before disturbances: 70 km/h.

The main scientific tools for ESC system performance evaluation are FOT (Field Operational Test) via naturalistic driving study in the U.S.A., Sweden etc. [5, 6], driving simulator [7], simulations in software [8], e.g. veDYNA and on-track testing by driving maneuvers at NHTSA [9, 10] and last but not least, accident analysis as summarized by Ferguson and Lie [11, 12] during which human injury and car damage level are mostly investigated and are directly used as benefit measures which are mentioned by Neale and Ferguson [5, 11]. A wide proliferation of ESC across the vehicle fleet has allowed its effectiveness evaluation in real world crashes involving actual cars with and without this technology. The underlying causes for these crashes are intended or unintended driver maneuvers. Furthermore, since nearly all the ESC effectiveness evaluation is in the perspective of avoiding (not merely mitigating) the possible 1st collision for the relevant car, their benefit analysis does not include any differentiation and categorization on "multiple-impact" and "single-impact" events.

Above all, unlike current ESC benefit analysis methods, a methodology is schemed out for future system (i.e. PISC) *benefit prediction*, during which the vehicle stability problems that are expected to be solved or attenuated by directional control should be unveiled and analyzed. At the current stage, it is considered as predominantly practical to use simulation software to initiate the performance evaluation. On-track testing and driving simulators are certainly promising candidates for benefit verification in the near future.

This paper presents a new method to quantitatively predict the benefit of a PISC function. The paper is organized as: an overview of the method for PISC benefit prediction is given in Chapter 2; Chapter 3 describes a function-oriented accident analysis so as to select representative accident scenarios (chromosome) mostly relevant to PISC; in order to gain deep understandings of the post impact vehicle dynamics, the individual accident cases selected for each chromosome are simulated with/without a conceptually designed PISC function in Chapter 4. In Chapter 5, the simulation results are analyzed including the observations of vehicle dynamical states on phase portrait; directional control problems causing 2nd impact and benefit measures for each chromosome are determined. The paper ends with Chapter 6 showing predicted benefits of PISC using the example controllers, during which the benefits are explicitly quantified for each measure of each chromosome; and conclusions in Chapter 7.

2. BENEFIT PREDICTION METHODOLOGY OVERVIEW

A time flow chart concerning one PISC-relevant car involved in multiple-impact events is illustrated in ***Figure 3***. The numbers (1, 2, 3 and 4) in this figure are time instants. The PISC preparation mentioned in this figure means the actions such as 1st impact characterization and brake system pre-charging. The benefit prediction in this paper is performed at the stage between Instant 3 and Instant 4.

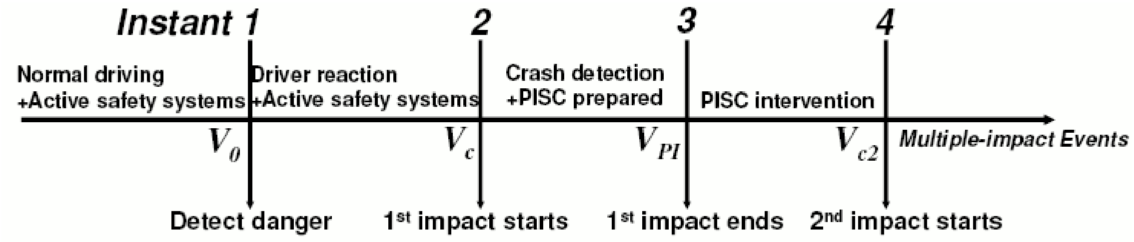


Figure 3 Time flow of multiple-impact events process.

The following picture depicts an overview of the PISC benefit prediction method (***Figure 4***). Except for the Risk Analysis, other critical steps have been iterated in several rounds. The box with thick line frame in the center displays the main work coordinating other subjects in this methodology. Representative scenarios using accident statistics and a vehicle dynamics simulation model are the key tools to perform the main loop highlighted in thick line. This loop is the core of the benefit prediction that generates the requirements on PISC function, so as to assist the function development. The requirements here refer to increasing benefit and decreasing risk. An example of such requirement is that lateral displacement during the 1st and 2nd impact should be reduced by 50%, compared with the one occurred in real accident. If no available safety system can fulfill these requirements, one needs to think about the modifications on the function and to develop an enhanced one to go through the benefit prediction main loop again. This type of iteration implies that the method hereby is regarding to an entire safety function design package, including control algorithms, actuators and sensors etc.

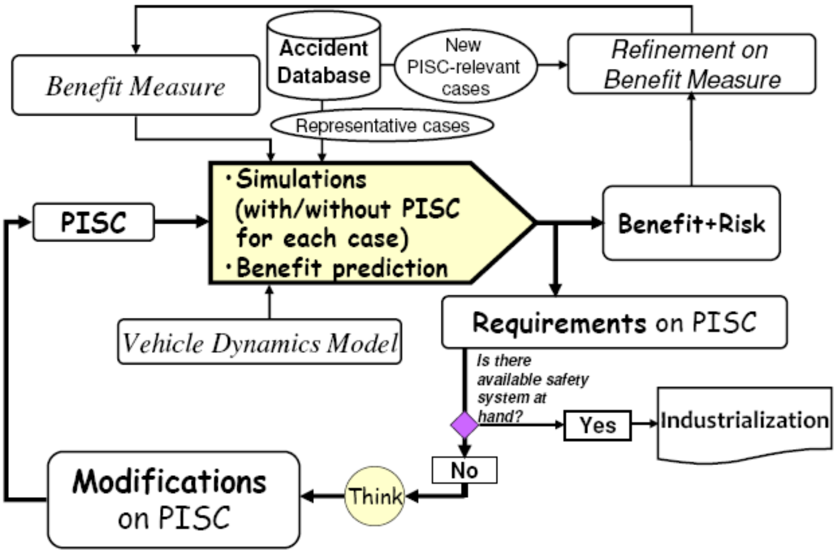


Figure 4 PISC benefit prediction methodology.

3. FUNCTION-ORIENTED ACCIDENT ANALYSIS

The Germany In-depth Accident Study (GIDAS) database is accessed which provides quantitative information about the post impact vehicle dynamics states via good-quality reconstructions in the PC-Crash simulation software [13]. The data from July 1999 to June 2007 is extracted which includes about 14600 passenger cars whose motions are completely reconstructed. Via the accident analysis concerning both post impact vehicle dynamics states and environmental factors, PISC-relevant cars are identified, categorized and prioritized. PISC-relevant here is defined as that positive safety benefit is foreseen given PISC interventions. Analysis on the negative safety benefit, i.e. risk, is delimited out of the present work.

3.1 Identification of PISC-relevant Cars

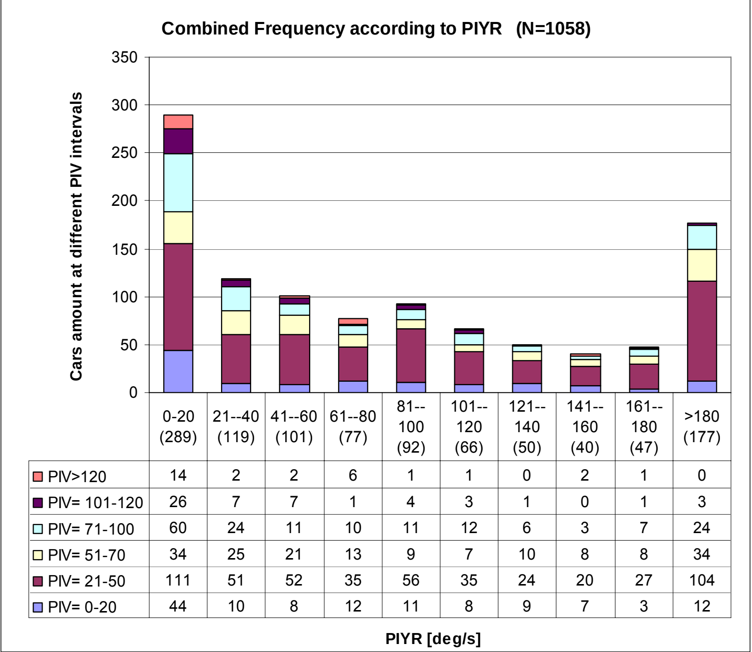
The identification enables deep understandings of the problematic areas that await PISC to mitigate. Necessary Search Criteria are applied to identify the PISC-relevant cars; those criteria are mostly out of consideration of vehicle stability control system characteristics, including controller and actuator capabilities.

- **Sufficient Dynamics:** Velocity before the 1st impact V_0>15 km/h. An even lower velocity is considered as controllable by drivers or the vehicle will intrinsically stop by itself within a very short time period.
- **Feasible Detection:** Change of velocity, ΔV, in the 1st impact >5 km/h. It is the minimal threshold for detection of crash by the inertial sensors on board.
- **Tire Road Contact:** Cars whose first event is **NOT** rollover. Tire forces commanded by PISC intervention are generated via contact with the ground, so after a rollover the PISC function can not have any benefit. To be mentioned, the cars running off road into mudded or grass field or ditch during the 1st and 2nd impacts are not excluded here, since there is no GIDAS code that can be directly used as search criterion. However, this population is estimated as small (less than 60 cars out of 995 cars).
- **Potential Benefit 1:** Cars involved in ***Multiple-Impact Events*** accidents**,** which is the baseline for PISC benefit prediction.
- **Potential Benefit 2:** Post Impact Velocity (PIV=$\sqrt{V_x^2 + V_y^2}$, at time instant 3 in ***Figure 3***) >20 km/h. *Cars with low PIV and low Post Impact Yaw Rate* (PIYR=Yaw Rate at time instant 3 in ***Figure 3***) will come to stop rather quickly that they can not be the host vehicle for PISC. *Cars with low PIV and high PIYR* will gain little effect from braking and steering interventions, due to rather fast heading angle change when the car almost standing still.
- **Reasonable Actuators:** Time to 2nd collision from 1st collision, TTC2 $\geq$ 0.3 s which approximately equals the fastest reaction time for nowadays actuators, i.e. Automatic Steering.

By applying the criteria above, a number of cars are excluded since they are considered as not addressable by a future PISC function. In the end, **995** out of 14600 cars are identified as PISC-relevant at this phase of the work.

3.2 Categorization of Accident Scenarios

Function-based categorization of accident scenarios is to determine the critical parameters which can together describe one representative accident case involving a PISC-relevant car. In the end, Post Impact Velocity, Post Impact Yaw Rate, Impact Area on cars, Road Type and Traffic Scenario/Road Layout are selected as the key factors. Firstly, PISC-relevant cars are categorized according to PIV and PIYR (***Figure 5***).



	0-20 (289)	21--40 (119)	41--60 (101)	61--80 (77)	81--100 (92)	101--120 (66)	121--140 (50)	141--160 (40)	161--180 (47)	>180 (177)
■ PIV>120	14	2	2	6	1	1	0	2	1	0
■ PIV= 101-120	26	7	7	1	4	3	1	0	1	3
■ PIV= 71-100	60	24	11	10	11	12	6	3	7	24
■ PIV= 51-70	34	25	21	13	9	7	10	8	8	34
■ PIV= 21-50	111	51	52	35	56	35	24	20	27	104
■ PIV= 0-20	44	10	8	12	11	8	9	7	3	12

Figure 5 Combined Frequency of Cars Involved in MIE according to PIYR.

Concerning the combined frequency shown above, PIV $\in$ [21, 50)&PIYR $\in$ [0, 120) and PIV $\in$ [21, 50)& PIYR>160 stand out as larger populations. Decision was made to cover all the PIYR intervals for the subsequent benefit prediction, since even for an active driver who has merely 0.5 s reaction time, the PIYR higher than 20 deg/s is already unmanageable without the assistance from preventive safety systems [8]. Hence, PIYR [deg/s] is categorized with respect to the actuator performance, available time between the 1st and 2nd collision (TTC2) and the heading angle change (≈body side slip angle directly after collision) before any intervention can be actuated:

- PIYR∈ [0, 150) deg/s (N=709, 4.9% of 14600 passenger cars)
  Heading angle change before steering intervention is less than 45 deg & TTC2>0.3 s; and/or heading angle change before braking intervention is less than 90 deg & TTC2>0.6 s.
- PIYR≥150 deg/s (N=152, 1.0% of 14600 passenger cars)
  Heading angle change before braking intervention is larger than 90 deg & TTC2>0.6 s.

Each of the three PIYR groups is split into two by different PIV categories: [21, 60] km/h and [61, 120] km/h.

The impact area is here defined as the area (Front, Side and Rear) on the vehicle that is subjected to the external impulses. The redistribution of tire forces is largely depending on the impact area and impulse angle (***Table 1***). Impulse angles are divided into three principal directions of force (PDOF): From Front; From Side and From Rear. As shown in ***Table 1***, for the 1st PISC-triggering impacts, those from the front onto the car's front area, from the side onto the car's side area, and from the front onto the car's side area are most common. Impact area but not PDOF is used as one of the five key factors for the prioritization in Section 3.3, since PDOF is captured by post impact vehicle dynamics states.

Table 1 Combined frequency of Impact Area and Principal Directions of force (PDOF): N=935. The bold numbers mark the 3 most common ones.

Impact Area→ PDOF↓	Front	Side	Rear	unknown	Total
From Front	**339 (36%)**	**123 (13%)**	0 (0%)	0 (0%)	462 (49.4%)
From Side	45 (4.8%)	**302 (32.3%)**	2 (0.2%)	0 (0%)	349 (37.3%)
From Rear	0 (0%)	38 (4%)	83 (8.9%)	3 (0.3%)	124 (13.3%)
Total	384 (41.1%)	463 (49.5%)	85 (9.1%)	3 (0.3%)	935 (100%)

Three main road types are usually distinguished: motorway, country road and urban road. The implied road features include: lane width, number of lanes, maximum permitted speed, traffic level, road side and edge condition, method of centerline separation (with/without crash barrier) and road quality. Table 2 below shows the amount of PISC-relevant cars in MIE accidents on each type of road.

Table 2 Frequency of Road Type: N=944.

Road Types	Motorway	Country road	Urban road	Others
Cars amount	258 (27.3%)	373 (39.5%)	298 (31.6%)	15 (1.6%)

Traffic Scenario/Road Layout is classified as continuous road and intersections. Different road layouts suggest different decisions on the driver desired path according to the traffic situation around, road direction at collision (straight or cornering), and vehicle motion direction at collision (straight or cornering) etc. It is found, **38%** of PISC-relevant cars were involved in MIE which occurred at intersection areas, within which 24% were outside the intersection square. Correspondingly **62%** occurred at continuous roads within which 60% were on the straight road. At the end of the categorization, **944** out of 14600 cars are the final population discerned as PISC-relevant.

3.3 Prioritization of Representative Cases

In accordance to the categorizations above, 14 groups of cars including information on the corresponding accident scenarios are selected as representatives of the 944 PISC-relevant cars, with respect to the combined frequency of the five key characteristics factors – prioritization (***Table 3***). These 14 representative scenarios are called "chromosome" which is a term inherited from gene terminology, since one representative scenario characterized by several factors is like a chromosome described by DNA. Lastly, via additional investigations of the database documents (photos, sketches, descriptions etc.) 17 GIDAS accident cases are selected for case-by-case studies in a MATLAB/Simulink vehicle simulation model with an example PISC function.

3.4 Influence of ESC on MIE Accidents

The accident analysis is performed based on the car population without differentiation of ESC-equipped or ESC-unequipped cars. It is because no statistical differences are identified between cars with and without ESC[1], either with respect to the probability of ending up in a secondary event or the frequency distribution of PIV and

---

[1] The results may not serve as strong evidence that ESC absolutely does not help to positively affect the secondary event, since 411 ESC-equipped cars are very few compared to 5024 ESC-unequipped cars from a statistical confidence perspective.

PIYR (***Figure 6***). Therefore, the influence of ESC on the MIE accidents is neglected.

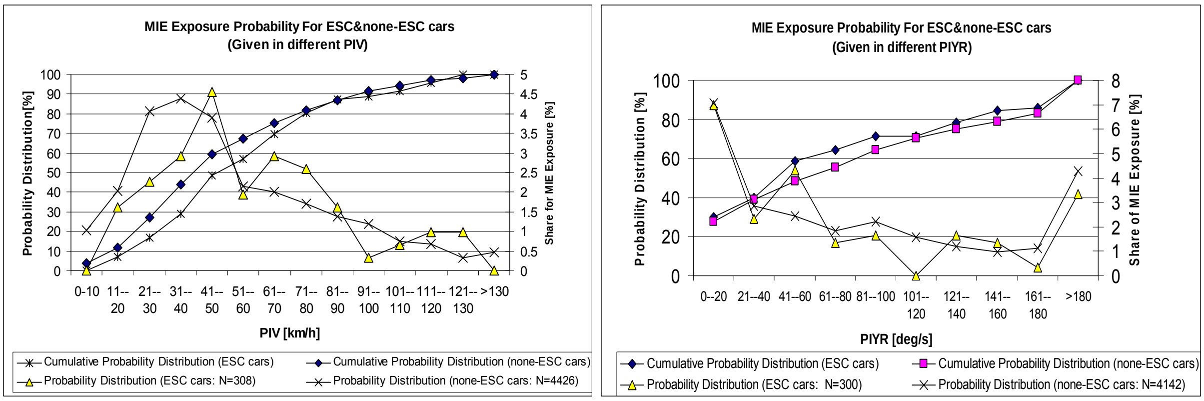


Figure 6 MIE exposure probability for cars with/without ESC, distributed over entire PIV or PIYR scale.

Table 3 Chromosomes of PISC-relevant cars.

Chromosome Group No.	**Key Characteristics**					**Car amount (frequency, N=944)**
	Vehicle Dynamics		***Impact***	***Environment***		
	PIYR [deg/s]	**PIV [km/h]**	**Impact Area**	**Road Type**	**Road Layout**	
1	≥150	21-60	Side	Urban road	Intersection	38 (4%)
2	0-150	21-60	Side	Urban road	Intersection	98 (10.4%)
3	0-150	21-60	Side	Country road	Continuous road	34 (3.6%)
4	0-150	21-60	Side	Country road	Intersection	37 (3.9%)
5	0-150	21-60	Front	Urban road	Intersection	37 (3.9%)
6	0-150	21-60	Front	Country road	Continuous road	42 (4.5%)
7	0-150	61-120	Front	Country road	Continuous road	42 (4.5%)
8	0-150	61-120	Front	motorway	Continuous road	42 (4.5%)
9	0-150	61-120	Side	Country road	Continuous road	33 (3.5%)
10	0-150	21-60	Rear	Any	Any	31 (3.3%)
11	0-150	61-120	Rear	Any	Any	36 (3.8%)
12	≥150	21-60	Front	Any	any	32 (3.4%)
13	≥150	61-120	Any	Any	Continuous road (mostly straight)	29 (3.1%)
14	0-150	21-60	Front	Country road	Intersection	29 (3.1%)

4. VEHICLE DYNAMICS SIMULATIONS WITH/WITHOUT PISC

One on-market sedan model is chosen as the research vehicle for the PISC benefit prediction, instead of copying the actual vehicles involved in each accident in GIDAS. If this car was subjected to similar circumstances as the car in the accidents, it is assumed that it would get the same post impact initial states, and hence, the comparison between the research car with and without PISC will reflect the real world benefit thanks to this future system. Additionally, the environmental factors such as traffic scenarios and road conditions are taken into account since they are also important with respect to the fidelity of the accident reconstruction. As stated in Chapter 2, the benefit prediction simulation starts at Instant 3 till Instant 4 as shown in ***Figure 3***. Thus the results from reconstructions of the pre-impact and impact phases in PC-Crash are adopted. Furthermore, the difficulty to incorporate different PISC controllers into black-box simulation software, e.g. PC-Crash, accounts for an important reason to use an open MATLAB/Simulink model to perform the simulations and comparisons with/without PISC. The model is a 3-DOF planar 2-track model which has 3 positions and 3 velocities on ground x-y plane, i.e. global longitudinal displacement X, lateral displacement Y, heading angle Ψ and vehicle-fixed longitudinal velocity V_x, lateral velocity V_y, yaw rate r. A model of relatively low complexity makes it easier to access and to vary the input accident data. It does neither model the wheel rotational dynamics nor the roll degree of freedom. Hence, the needed initial values of vehicle states are fewer and it becomes practical to efficiently simulate various real world accident scenarios. The equations of motion are shown in the Eq.1 below.

$$\begin{cases} m\cdot(\dot{v}_x - v_y\cdot r) = F_{xFL} + F_{xFR} - (F_{yFL} + F_{yFR})\cdot\delta_f + F_{xRL} + F_{xRR} - (F_{yRL} + F_{yRR})\cdot\delta_r \\ m\cdot(\dot{v}_y + v_x\cdot r) = F_{yFL} + F_{yFR} + (F_{xFL} + F_{xFR})\cdot\delta_f + F_{yRL} + F_{yRR} + (F_{xRL} + F_{xRR})\cdot\delta_r \\ I_{zz}\cdot\dot{r} = l_f\cdot\left(F_{yFL} + F_{yFR}\right) - l_r\cdot\left(F_{yRL} + F_{yRR}\right) + l_f\cdot(F_{xFL} + F_{xFR})\cdot\delta_f - l_r\cdot(F_{xRL} + F_{xRR})\cdot\delta_r + \\ \qquad + \frac{t}{2}\cdot(F_{xFR} - F_{xFL}) + \frac{t}{2}\cdot(F_{xRR} - F_{xRL}) + \frac{t}{2}\cdot(F_{yFL} - F_{yFR})\cdot\delta_f + \frac{t}{2}\cdot(F_{yRL} - F_{yRR})\cdot\delta_r \end{cases} \quad \textbf{(1)}$$

For the PISC benefit prediction purpose, a simplified version of Magic Formula Tire Model is implemented (Eq.2), derived from pure lateral slip tire model in Pacejka's book [14].

$$F_y(\alpha) = -\mathrm{sign}(\alpha)\cdot D\cdot\sin\{C\cdot\arctan[B\cdot\alpha - E\cdot(B\cdot\alpha - \arctan(B\cdot\alpha))]\} \quad \textbf{(2)}$$

Where the peak tire lateral force $D = \sqrt{(\mu\cdot F_z)^2 - F_x{}^2}$. The tire model constants are tuned in accordance with the tire of a normal passenger car. The tire forces are analyzed throughout the entire range of tire side slip angle from -180 deg to +180 deg, representing the extreme rotational spinning and lateral sliding motion after an impact. Furthermore, the brake actuator dynamics is simulated that the maximum available braking force and its rising and falling rate are all limited. The model is validated by comparing vehicle dynamics states and tire forces with those from simulations in veDYNA [15], without any active safety function interventions.

Two control strategies counteracting the yaw motion and reducing the risk of departing from the driver desired path are implemented into the simulation model. One is differential braking (DB) controller which commands to brake one side wheels to reduce the yaw rate; the other is to fully brake and lock the front (leading-motion) axle (LF) whenever the yaw rate exceeds a certain threshold so as to reduce the front cornering stiffness and thus to direct the car neutrally forward. They are used as examples to demonstrate the PISC benefit prediction method and to investigate the potential of braking intervention stabilizing the car after the 1st impact. For detailed information about the controllers, see Reference [16].

5. ANALYSIS FOR PISC BENEFIT PREDICTION

5.1 Post Impact Stability Analysis Method and Tools

A case-by-case simulation and analysis is performed so as to determine the benefit measures that are used for PISC benefit prediction as well as identifying the directional control problems causing 2nd impact in MIE accidents. Four main materials are therefore prepared for this benefit prediction: reconstructed vehicle motion (X, Y, Ψ, V_x, V_y, r) during Instant 3 and Instant 4 using the Simulink model; on-scene accident sketch by GIDAS accident investigators; predicted motion at the presence of PISC; phase portrait depicting the instantaneous yaw rate, lateral velocity and tire side slip angles. Path plots from the simulations are well matched with the accident sketches and the ones without and with example PISC controllers are compared.

The phase portrait with phase curves corresponding to different yaw rate (r) and lateral velocity (V_y) is produced for each chromosome car, with the secondary axis being tire side slip angles: α_f and α_r. Since it is not possible to make the scales of α_f and α_r axis which are changing over the time, the vehicle initial α_f and α_r are noted on the title of each portrait. Furthermore, with respect to the lateral tire force $F_y(\alpha)$ curve, one critical corner representing the lateral force peak saturation point is marked on the phase portrait. It is to identify whether the tire is within linear or nonlinear region concerning to its slip angle. Hereby, three points are marked: initial states if F_y is saturated; states at the ½ of TTC2 if F_y is saturated without PISC; states at the ½ of TTC2 if F_y is saturated with PISC. One of these three points represents one corner of the critical square concerning to the linear region of building up tire lateral force. On the two curves of state trajectories with and without PISC, the initial states are marked with circles; the states at ¼ of TTC2 are marked with diamonds; the states at ½ of TTC2 are marked with stars. By tracing on these marks, the vehicle states development against time are identified. See ***Figure 7*** and ***Figure 8*** for an example of the four main materials used for post impact stability analysis (Chromosome 9). ***Figure 8*** shows a vehicle (host vehicle) firstly hit in the side by another vehicle (bullet vehicle). The motion after the first impact results in a second event, which is a collision for the host vehicle with a stationary object (tree) closely outside the road edge.

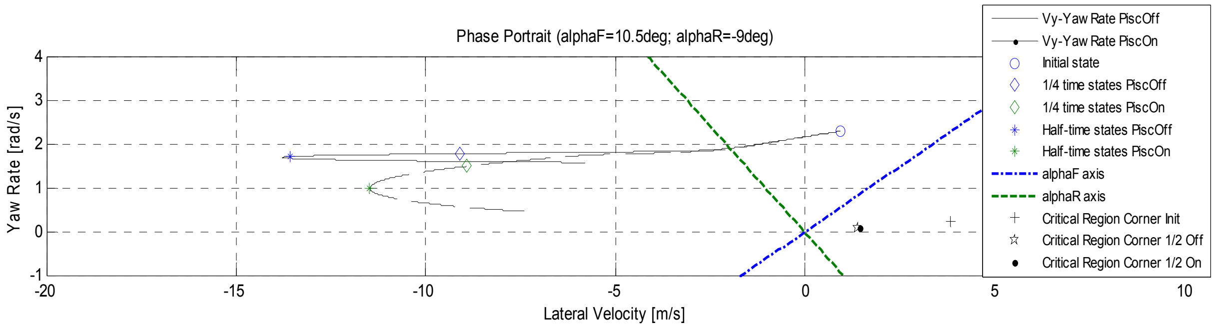


Figure 7   Vehicle stability analysis using phase portrait: Chromosome 9.

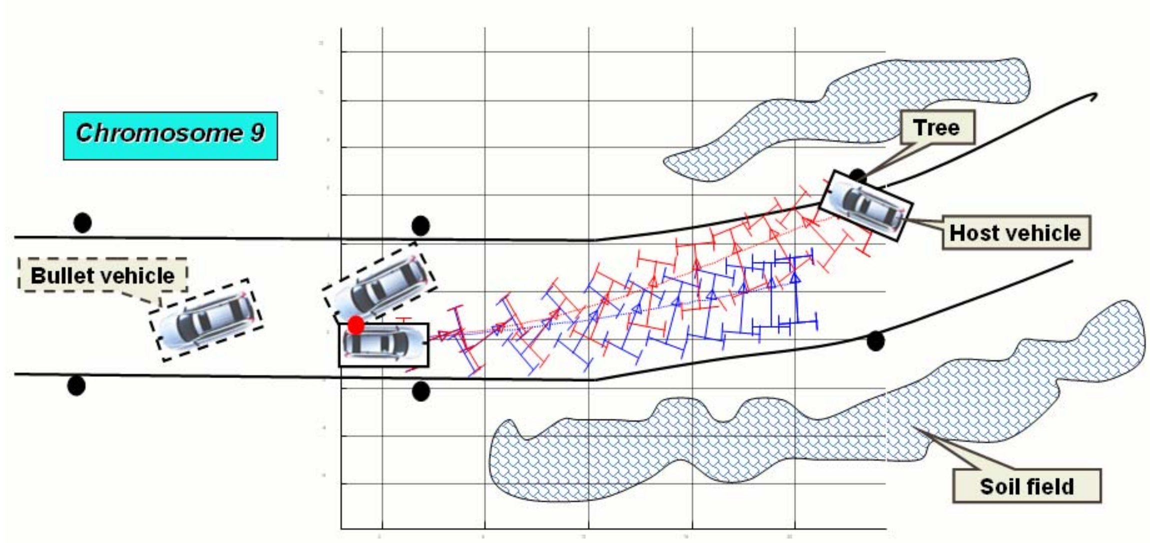


Figure 8   Path plots with (blue car) and without (red car) PISC over the on-scene sketch: Chromosome 9.

Generally, the parameters selected as benefit measures for PISC are: lateral displacement at TTC2 (Y); yaw angle at TTC2 (Ψ); yaw rate at TTC2 (r); front and rear axle side slip angle at TTC2 (α_f, α_r); secondary event avoided or not (Y/N); kinetic energy when the car has traveled the same distance, if secondary event is unavoidable (W).

5.2 Directional Control Problems Causing 2nd Impact

In this section, the directional control problems giving rise to the secondary impact are identified and categorized. Also, a scheme of controller selector is proposed for integrated control strategies during different phases from the 1st to the 2nd impact. A set of benefit measure is thus assigned to each severity level of the directional control problems.

The directional control problems are classified as three different severity levels. The lightest situation is Trajectory Deviation problems which require lateral displacement and yaw angle correction to a large extent. The intermediate group is Moderate Instability problems that yaw rate correction is mostly needed. The severest group is called Severe Instability that aggressive interventions on yaw rate, side slip angle and thus lateral displacement are highly required.

It is expected that PISC can switch among a certain number of controllers dependent on different post impact (PI) situations. It is favorable to have a less complex function package so as to reduce the number of times of switching. In this case, the PI problems will be solved by PISC in a hierarchy with decreasing severity sequence: Severe

Instability – Moderate Instability – Trajectory Deviation. Thereafter, three different types (***Table 4***) of controllers are switched on at each phase. A scheme of controller selector is thus configured and the general motivations for assigning each measure to each problem level are populated into the center cells of ***Table 4*** as well.

Table 4 Benefit measures for varied 2nd impact problems and scheme of controller selector.

Problem causing 2nd Impact → Benefit Measures↓	**Trajectory Deviation (T)**	**Moderate Instability (S)**	**Severe Instability (S+)**
Kinetic energy, W	*Increased Severity in 2nd Impact*	*Increased Severity in 2nd Impact*	*Increased Severity in 2nd Impact*
Lateral deviation from path predicted before 1st impact, Y	*Hit object beside lane/road*	*Hit object beside lane/road*	*Hit object beside lane/road*
Yaw angle change from before 1st impact, Ψ	*Difficulty in getting back to desired trajectory via path control*	–	–
Yaw rate, r	–	*Difficulty in getting back to desired trajectory via stability control*	*Difficulty in yaw elimination and back to desired trajectory*
Side slip angle front axle, α_f	–		–
Side slip angle rear axle, α_r	–		–
Selected Controller	Differential Braking	Differential Braking	Lock Front

In ***Table 4***, a number of selected benefit measures are assigned to each of the identified directional control problems, during which phase portrait like the one in ***Figure 7*** is utilized and a general rule is defined:

> *Without PISC, if at ½ of TTC2, the car's instantaneous states point is outside of the "Tire Side Slip Angle Square" defined by the "critical region corner at ½ of TTC2", its tire forces are saturated out to the non-linear region on the curve. In this case, the car is subjected to either "Moderate Instability" or "Severe Instability" problems. Otherwise, mere path control strategy is required to solve the "Trajectory Deviation" problem. Meanwhile, cars with "Severe Instability" problems are those with PIYR≥150 deg/s and thus the rest are classified as with "Moderate Instability" problems.*

As shown in the example (***Figure 7***), the states point indicated by "*" point at ½ of TTC2 is outside the critical square whose corner is indicated by a five-tip-star. The phase portrait also shows that the initial yaw rate is less than 150 deg/s. The tire side slip angles grow fast due to high initial yaw rate. These features are typical for all the cars in Moderate Instability category and thus yaw rate and tire slip angles are selected as benefit measures. By looking into the matched path plots with and without PISC (DB controller for Chromosome 9, see ***Figure 8***), the lateral displacement and kinetic energy clearly play critical roles in the consequence of the secondary event. On the other hand, the yaw angle change is largely reflected by the lateral displacement and the yaw rate conditions and rather less relevant for the PISC-relevant car on the scene shown in ***Figure 8***.

Finally, in addition to the four main materials elaborated above, narrative descriptions on the accident circumstances and other reconstructed parameters such as impact point, impulse angle, travelling distance and rotation during the 1st and 2nd impact etc are investigated; the problems giving rise to the secondary event for the representative PISC-relevant car in each chromosome are discovered and assigned with one of the three levels listed in ***Table 4***. Hereby, the corresponding benefit measures, as well as the anticipations for future PISC control variables can be determined. In all, the overall characteristics for each chromosome are unveiled and the requirements of PISC function design are generated.

6. PREDICTED PISC BENEFITS RESULTS

6.1 Benefit Quantification

As stated above, improvement on the post impact vehicle dynamics, i.e. benefits are quantified on each selected benefit measure. Hereby, the benefit is expressed in positive percentages (Eq.3).

$$Benefit\ (\%) = \frac{\left|Measure\right\|_{PiscOff} - \left|Measure\right\|_{PiscOn}}{\left|Measure\right\|_{PiscOff}} \cdot 100 \qquad \textbf{(3)}$$

The absolute values of all selected measures are utilized, so as to assess the degree of deviation from driver desired values which are set as zero. Particularly, for tire side slip angles, they are assigned from $0° \text{ to } 90°$, since $90°$ is normally concerned as the most severely instable situation, in either forwarding or reversing motions.

In the present work, apart from the quantification of benefit for each measure, no further computations are performed taking the frequency of each chromosome into account. Furthermore, in order to correlate the individual improvements on vehicle dynamics variables with the real world physical benefits, which will directly contribute to the increase of PISC benefit in one accident, one ***common scalar*** measure should be invented. As a preliminary proposal, injury severity level can be used as this common measure. In this case, for instance, the yaw angle at TTC2 will affect the impact area which will then cause the stratified injury levels.

6.2 Benefits for Each Chromosome Case

By using the quantification formula above (Eq.3), the safety benefit for each chromosome case is predicted (***Table 5***). In the table, the secondary impact is avoided if the kinetic energy reduction *W* is noted as 100%. The results of the example case in ***Figure 7*** and ***Figure 8*** are shown in the row of Chromosome Group No.9.

Table 5 PISC Benefit Prediction for Each Chromosome.

Chromosome Group No.	Current Control Strategy	Future Control Variable Proposals	Problem causing 2^{nd} Impact	Benefit (%) for each measure in Individual Case studies (Benefit=(M0-M1)/M0*100)					
				Y	r	ψ	α_f	α_r	W
1	LF	$r + Y$	**S+**	51.3	-76604[2]				100.0
2	DB	$\psi + Y$	**T**	13.4		2.3			22.7
3	DB	$\psi + Y + (r)$	**T**	17.9	85.7	19.5			45.4
4	DB	$\psi + Y$	**T**	18.8		6.4			48.7
5	DB	$\psi + Y$	**T**	21.3		-1.0			47.3
6	DB	$\psi + Y + (r)$	**T**	40.0	100.0	39.0			48.7
7	DB	$r+Y+(\alpha_f+\alpha_r)$	**S**	-37.9	91.5		-87.4	-63.1	20.6
8	DB	$r+Y+(\alpha_f+\alpha_r)$	**S**	-9.2	97.0		-247.8	-124.0	20.9
9	DB	$r+Y+(\alpha_f+\alpha_r)$	**S**	47.8	70.2		-214.8	-87.8	79.4
10	DB	$r+Y+(\alpha_f+\alpha_r)$	**S**	48.0	92.0		-71.1	-3.0	100.0
11	DB	$r+Y+(\alpha_f+\alpha_r)$	**S**						
12	LF	$r + Y$	**S+**	-32.3	21.3				72.9
				19.1	20.5				52.7
13	LF	$r + Y$	**S+**	5.2	-0.9				32.1
14	DB	$\psi + Y + (r)$	**T**	8.2	-70.0	-3.5			30.4

---

[2] Benefit of this measure without PISC (M0) is approx. zero.

In sum, combining the selected measures and the corresponding benefits for each chromosome, the findings are:

1. The reduction of *kinetic energy W* is from 20% to 100%. This indicates that PISC will make the injury risk level lower.
2. For chromosomes (No.2, 3, 4, 5, 6, and 14), the cars are exposed to "Trajectory Deviation" problem. Clearly that the yaw rate and side slip angle diminishes quite fast to zero within ½ of TTC2, even without any function intervention. In this case, the rotation between two impacts is normally less than 45 degrees. The DB controller would stop intervention since yaw rate error ($r_{error} = \left\| |r| - |r_{ref}| \right\|$) becomes smaller than the predefined threshold. However, even if the instability is counteracted by PISC, differential braking for yaw angle correction or full-wheels-braking is still required to attenuate the trajectory deviation furthermore in order to avoid the 2nd impact.
3. For chromosomes (No.7, 8, 9 and 10), the cars are exposed to "Moderate Instability" problem. The *yaw rate r* is reduced efficiently by the DB controller. *Lateral displacement Y* and *kinetic energy W* are the critical measures of the accident severity. The controller is rather beneficial to chromosome 9 and 10, but much worse for chromosome 7 and 8, regarding the benefit of lateral displacement. The *tire side slip angle* changes abruptly and stays high even if the yaw rate has diminished quickly. In this case, the controller lessens the spinning at the sacrifice of lower side slip angles.
4. For chromosomes (No.1, 12 and 13), the cars are exposed to "Severe Instability" problem. The requirement to efficiently reduce *yaw rate* is highly challenging. The *kinetic energy* is reduced to a large degree. However, since "Lock Front" is an aggressive open-loop control strategy, the resultant lateral displacement is dependent on the vehicle initial states, i.e. yaw rate, side slip angle etc. Overall, the benefits on *lateral displacement* and *yaw rate* are not yet sufficient.
5. There merely exists a few seconds during which PISC can take over the control. When the car regains stability, no matter in terms of longitudinal or lateral dynamics, the driver should have the capability to control the car again, either by smoothly steering to correct the direction or by active braking to avoid the 2nd impact. Otherwise, other active safety systems on board, e.g. Collision Mitigation by Braking (CMbB) etc, should be activated.

7. CONCLUSIONS

One method for benefit prediction of passenger car post impact stability control (PISC) system is formulated, based on accident statistics and vehicle dynamics simulations. The problematic areas, including both post impact vehicle dynamical situations and environmental surroundings for a PISC solution, are identified and representative accident cases are selected. A way to analyze the cases is derived, aiming at determine and quantify benefit measures for each case. A PISC function with two example controllers is preliminarily applied to test and demonstrate the proposed methodology for the benefit prediction. Depending on varied types of problems during different stages after the 1st PISC-triggering impact, different benefit measures are used. The scheme of a controller selector is proposed. Furthermore, it is found that reduction of kinetic energy is quite beneficial and feasibly achieved by aggressive braking interventions. It is also found that effective path control would be particularly beneficial under post impact circumstances.

ACKNOWLEDGEMENTS

The GIDAS data, which was analyzed by the authors of the present thesis, was kindly provided by Ford of Europe Company. For the present study, accident data from GIDAS (German In-Depth Accident Study) was used. GIDAS is the largest in-depth accident study in Germany. The data collected in the GIDAS project is very extensive, and serves as a basis of knowledge for different groups of interest. Due to a well defined sampling plan, representativeness with respect to the federal statistics is also guaranteed. Since mid 1999, the GIDAS project has collected on-scene accident cases in the areas of Hannover and Dresden. GIDAS collects data from accidents of all kinds and, due to the on-scene investigation and the full reconstruction of each accident, gives a comprehensive view on the individual accident sequences and its causation. The project is funded by the Federal Highway Research Institute (BASt) and the German Research Association for Automotive Technology (FAT), a department of the VDA (German Association of the Automotive Industry). Use of the data is restricted to the participants of the project. However, to allow interested parties the direct use of the GIDAS data, several models of participation exist. Further information can be found at http://www.gidas.org.

REFERENCES

[1] J. Zhou, H. Peng and J. Lu: *Vehicle Stabilization in Response to Exogenous Impulsive Disturbances to the Vehicle Body*, Vehicle System Dynamics, 46:1, 3-15, 2008.

[2] P.A. Fay, R. Sferco and R. Frampton: *Multiple impact crashes- consequences for occupant protection measures*, Proceedings of IRCOBI Conference, Isle of Man, 2001.

[3] K. Langwieder, A. Sporner and W. Hell: *RESICO-Retrospective Safety Analysis of Car Collisions Resulting in Serious Injuries*, GDV 9810, Munich, Germany, 1999.

[4] W. Haddon Jr.: *The changing approach to the epidemiology, prevention, and amelioration of trauma: the transition to approaches etiologically rather than descriptively based*, American Journal of Public Health, Vol. 58, No. 8, pp. 1431–1438, 1968.

[5] V.L. Neale, T.A. Dingus, S.G. Klauer, J. Sudweeks and M. Goodman: *An Overview of the 100-Car Naturalistic Study and Findings*, Paper Number: 05-0400, pp. 5, U.S.A., 2005.

[6] Vehicle and Traffic Safety Centre, Chalmers (SAFER): *Test Site Sweden Field Operational Test Final Report 2008*, www.chalmers.se/safer, 2008-10-11.

[7] E. Pettersson and D. Tidholm: *Vehicle Stability Control for Side Collisions by Brake and Steering Wheel Torque Superposition*, Department of Signals and Systems, Chalmers University of Technology, Master's Thesis EX031/2007, ISSN 1652-8557, Gothenburg, Sweden, 2007.

[8] M. Thor: *The Efficiency of Electronic Stability Control after Light Collisions*, Department of Applied Mechanics, Chalmers University of Technology, Master's Thesis 2007:02, ISSN 1652-8557, Gothenburg, Sweden, 2007.

[9] National Highway and Traffic Safety Administration: *Federal Motor Vehicle Safety Standards – Electronic Stability Control Systems – Controls and Displays*, *NHTSA report*, NHTSA, No. 200727662, 2007.

[10] G.J. Forkenbrock, D.H. Elsasser, B.C. O' Harra and R.E. Jones: *Development of Electronic Stability Control (ESC) Performance Criteria*, National Highway and Traffic Safety Administration (NHTSA) Report, Washington D.C., U.S.A., 2006.

[11] S.A. Ferguson: *The Effectiveness of Electronic Stability Control in Reducing Real world Crashes: A Literature Review*, Traffic Injury Prevention, 8:329–338, 2007.

[12] A. Lie, C. Tingvall, M. Krafft and A. Kullgren: *The Effectiveness of ESC (Electronic Stability Control) in Reducing Real Life Crashes and Injuries*, 19th International Technical Conference on the Enhanced Safety of Vehicles Conference (ESV), Paper number 05-0135, June 2005.

[13] S. Datentechnik: *PC-Crash Technical Manual*, DSD, A-4020 Linz, 1996.

[14] H.B. Pacejka: *Tire and Vehicle Dynamics (2nd Ed.)*, Society of Automotive Engineers, Inc. SAE ISBN 0 7680 1702 5, Warrendale, PA, pp. 90-190, 2006.

[15] Tesis DYNAware GmbH: *The veDYNA Product Catalogue*, http://www.tesis.de/en/index.php?page=544 (2008-11-16).

[16] D. Yang: *Method for Benefit Prediction of Passenger Car Post Impact Stability Control.* Department of Applied Mechanics, Chalmers University of Technology, Master's Thesis 2009:06, ISSN 1652-8557, Gothenburg, Sweden, 2009.