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Adaptive Brake By Wire

From Human Factors to Adaptive Implementation

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General overview

Brake systems are undergoing radical change. Decisions to apply (or release) brakes are being made automatically by computer-controlled systems (e.g., ABS and ACC). The type, complexity and shear number of such automatic systems is growing. To enabled automatic control, electro-hydraulic valves acting under computer control have been introduced to the traditional hydraulic systems. Electro-hydraulic brake-by-wire has been introduced, and in the foreseeable future, the brake application system is likely to become predominately electro-mechanical, largely doing away with hydraulic components (NHTSA, 2005).
In recent years, the friction brake and the hydraulic actuation system have remained overwhelmingly dominant, but computer-controller "intelligent" systems and are being given increasingly important (and numerous) roles in deciding how and even when to apply brakes. This trend will continue and may lead to the demise of the traditional hydraulic system in favour of the so-called brake-by-wire systems: systems using electrohydraulic actuation and, eventually, electro-mechanical actuation. Recently, regenerative brakes have appeared in small numbers (in hybrid and fully electric vehicles) to supplement the friction brake. The trend is likely to continue, albeit slowly. There may be some very long-term potential for reversal of these roles, i.e., motors acting as regenerative brakes supplying the primary braking effort with smaller friction brakes playing a supporting role. Computer-controlled brake application has become commonplace. Some of these systems modify braking initiated by the driver. Anti-lock braking systems (ABS) and traction control systems apply (or release) hydraulic pressure to prevent excessive (positive or negative) wheel slip. Brake-assist systems accelerate (in time), and may also raise the level of, brake application to improving emergency brake applications. Current brake-assist systems do so by altering the behaviour of the vacuum booster when the driver applies the brake more rapidly than normal. Other automatic systems apply the brake(s) on their own (as apposed to modifying driver-initiated braking). Stability enhancement systems apply individual wheel brakes to prevent pending yaw instability or can apply brakes generally to lower speed for the purpose of avoiding excessive lateral acceleration and, hence, rollover. More recent versions of Adaptive Cruise-Control (i.e. ACC) systems apply service brakes to adjust speed and maintain headway relative to a leading vehicle. The future is likely to see expanded use of similar automatic brake application in the forms of various crash mitigation and crash-avoidance systems.
Traditionally, the primary control interface between the driver and the brake system has been the brake pedal: a mechanical link through which the driver energizes the hydraulic master cylinder with forces applied by the foot. A secondary control interface is the parking-brake actuator, usually a hand operated lever or another foot pedal. Dash mounted warning lights provide an interface by which the driver can monitor the health of the brake system and its auxiliary elements. Finally, the rear-mounted brake lights constitute and advisory interface with other drivers regarding braking activity of the host vehicle.
The introduction of automatic braking functions has already resulted in some changes to the behaviour of these interfaces. The introduction of ABS effected the driver's primary interface with the brake system in that pressure pulses induced by the actions of some ABS systems are felt in the form of vibration or pulsation of the brake pedal. This was initially a source of some confusion for drivers but apparently has not been a major problem. Brake-assist systems now on the market

also provide a distinctly different pedal feel when the system is activated as compared to pedal feel during normal applications.

The introduction of brake-by-wire systems has the potential for major changes to the primary driver/system interface. In theory, brake-by-wire does not require any forceful actuation by the driver, thereby eliminating the basic reason for actuation via a foot pedal. While the primary actuator could certainly remain as a pedal with either a displacement or pedal-force transducer, it could just as well be a hand-operated lever (joystick) or button as has been demonstrated in some experimental systems. On the other hand, in the foreseeable future, it is apparent that manufacturers have no plans to launch such changes. Indeed, the greater concern seems to be the desire to maintain a traditional pedal feel as brake-by-wire systems evolve. Moreover, manufactures will favour maintaining at least two-wheel hydraulic brake actuation as a fail-safe backup system for some time. Thus, the master cylinder is likely to remain for some time as part of a backup system.

The electro-mechanical form of brake-by-wire also offers obvious motivation for altering parking-brake application. In many cases the same electro-mechanical device used to apply the wheel brake for service braking would be appropriate for applying the brake in emergency or parking situations. (Separate electric parking brake applicators have already been developed). With electric application, all of the numerous mechanical components associated with parking brake application could seemingly be replaced with little more than an electric switch and some wiring, implying very attractive weight and cost savings.

If we assume that “the brake system” encompasses all of the automated systems that apply brakes, the monitoring interface between the driver and that brake system is becoming far more extensive and complex. The common “ABS” warning light was the first small step in this progression. This warning light provides a simple binary message regarding the general health of the system: either the ABS is properly operational or it is not. On the other hand, ACC systems, for example, have rather elaborate dash-board displays that not only indicate general system health, but provide continuing information on the current operating state on a moment-to-moment basis. These visual displays may indicate various driver-selected settings as well as monitoring system status (e.g., target vehicle recognized/not recognized). Additional visual displays and/or audible warnings indicate that the driver must take over the braking task. As they become available, forward-crash avoidance, lane-departure avoidance and other such systems will presumably have similarly elaborate performance-monitoring interfaces (NHTSA, 2005).

Finally, vehicle brake systems interface not only with the driver of the vehicle on which they are mounted, but also with the drivers of following vehicles. Previously, the decision as to when to turn on brake lights was rather straight forward: when the driver applied the brakes. The means to do so was similarly simple: with a switch activated by initial brake-pedal motion or initial brake-pressure rise. Whether or not automatic brake application should be accompanied by brake-light actuation is not always so clear cut. The proliferation of automatic systems for applying brakes may raise this same question again in differing contexts. In any case, the means by which brake lights are actuated cannot remain so simple. Some set of brake actuations must result in brake lights turning on; others must be filtered out so that do not cause the brake lights to illuminate (NHTSA, 2005).

The brake itself is also changing. Electric regenerative braking has been introduced as augmentation to the friction brake to improve the energy efficiency of electric and hybrid vehicles.

Hydraulic regenerative braking may be introduced soon. In the long term, regenerative braking could become the primary braking mechanism(NHTSA, 2005).
Experimental results from test user tests confirm the need of a driver dependant adaptive behaviour of the brake pedal characteristic and of a "smart" brake pedal for future brake-by-wire system. That could also fit theoretical considerations for the enhancement of active safety as significant improvement of the drivers condition during braking and an increase of the braking stability of the vehicle seem possible.
Furthermore, anthropometrical and physiological considerations lead to a "personalized brake pedal as, with the view of brake-by-wire systems, a driver individual and braking situation dependant brake pedal characteristic is possible in principle.

Introduction

The introduction of brake by wire system is replacing the traditional mechanical control systems with ECUs and active systems. This process is raising the need to reproduce feelings of eliminated static mechanical components (i.e. hydraulic fluids, pumps and cylinders). Thanks to electromechanical actuators and human-machine interfaces (i.e. active pedal) it is possible to reproduce such feelings and, therefore, be able to change their features.
This process makes possible customization of the pedal feelings depending on several factors (i.e. surrounding braking scenario, driver characteristics, race vs day-by-day driving condition). Since braking maneuvers are typically critical and, especially, involve the driver, the design and development of brake by wire system should start from human factors considerations in order to increase acceptance and braking effectiveness.
The objective of this research is to define methods and strategies for designing adaptable pedal brake feeling. The methods shown in the following chapters could be applicable in order to find different solutions basing on the requirements of the specific project. In fact, the strategies proposed in the research are not restricted to a certain project but they are potentially pliable to others environment, making the adaptive approach global. Driver acceptance and braking effectiveness could be highly improved by means of adaptive pedal feelings.
The starting points of this research are the humans factors in the braking domain. Literature and relevant studies have been taken into consideration to put into evidence human mechanisms and behaviors during braking phases. Braking process has been analyzed in chapter 1, as well which parameters affects, and how, the pedal feelings (chapter 2). Once shown the basis of the human factors as well the behaviors of the pedal feelings in function of own characteristics, the research focuses on general aspects about the design of the pedal feeling (chapter 3). Within outputs of the chapter 3, there are the considerations about the scenario-related behavior of the pedal and how the brake pedal should work. On such basis, the research shows two main results: braking scenario and pedal feeling curves, respectively in paragraph 3.6 and chapter 0. Regarding braking scenario, different use cases are described in function of data available inside the vehicle. In the end, these use cases have been clustered depending on own characteristics. Concerning the pedal feelings curves, 4 different pedal feelings have been designed: the curves describe the behavior of force as well the deceleration, both in function of brake pedal travel. Once defined the curves, for each use case has been associated one pedal feeling (curve). The research continues on the implementation of a Matlab®/Simulink®/Stateflow® model for the use case recognition (chapter 5). Basing on the data available on a standard vehicle, the model is able to find out in which use case the vehicle/driver is facing of (parking, low speed maneuvers, emergency, downhill, and so on). Once it finds out the scenario, the model applies the most appropriate pedal feeling curve, calculating both pedal force feedback and deceleration needed. Finally, the model has been deployed on DSPACE hardware in order to check its working principles. With the purpose to debug and validate the model, some trials have been performed in order to collect real data on real vehicle (chapter 0). Thanks to these data collection, it has been possible to adjust and validate the scenario recognition, the force feedback calculation and the deceleration needed. It is important to underline that the model, especially the “Observer”, has been designed and validated basing on data collected in a standard vehicle: no special equipment are necessary (except for road slope):

all the data are provided via standard CAN bus. One other important point is the presence or not of ADAS: in this case the vehicle is not equipped with ADAS. However, the implementation takes into consideration the availability (or not) of such systems, like automatic parking system and information on the time to collision. Figure 1 shows the workflow described so far.

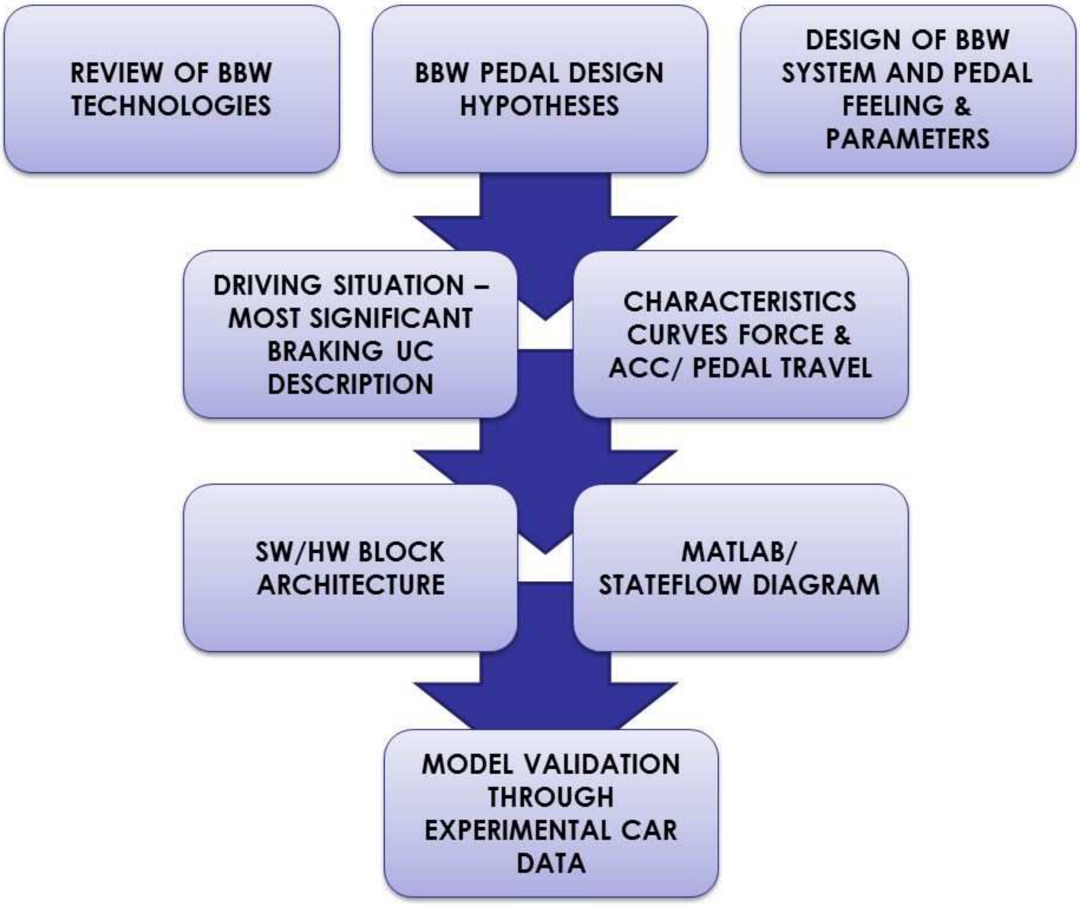


FIGURE 1: RESEARCH WORKFLOW

1. Braking process from the Human Factors point of view

1.1. The braking process and the user-related aspects

The basic demands in the brake system are the provision of an optimal responsiveness and decelerations behaviour in all driving and environmental conditions. Besides the objective measurable variables, the customer's subjective perception during the braking process is of particular importance when rating the quality of braking behaviour.
The layout aims at giving the customer's confidence in the safety level and the performance of their car in terms of positive distinct features. Brake pedal felling, responsiveness, and controllability are fundamentally important besides the basic performance and tracking stability during braking process.
The brake pedal represents the driver's central interface for controlling the braking process. Vehicle deceleration and pedal force characteristics are the important responses to the driver providing the subjective impression of responsiveness and controllability. The operating range starts from soft comfort braking to normal braking to standstill and full braking in dangerous situations.
The system technical presentation shows that the layout and optimization of the brake pedal feeling and thus the responsiveness require a detailed consideration of the overall brake system.

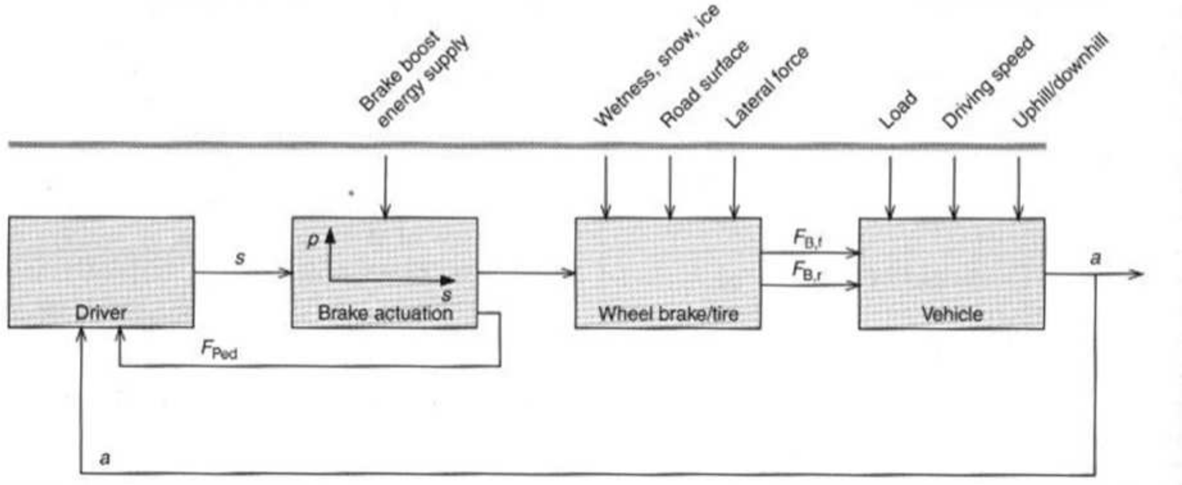


Figure 2: Control Loop Driver-Vehicle During Braking Process (Breuer , Bill, 2008)

After user perception and reaction, every braking action can be decomposed according to the following 5 phases:
- Accelerator release;
- Foot displacement from accelerator pedal to brake pedal;
- Hit of the brake pedal (generally in the 100 to 200 first ms) ;
- Regulation of applied braking force;
- Brake pedal throttle off.

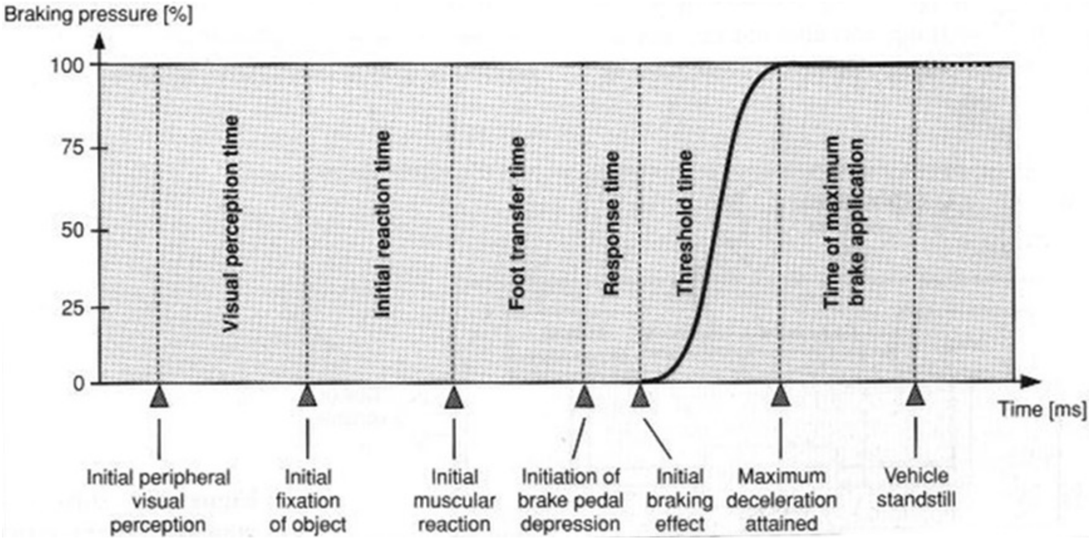


Figure 3: Time Phases Of An Emergency Brake Action (Breuer , Bill, 2008)

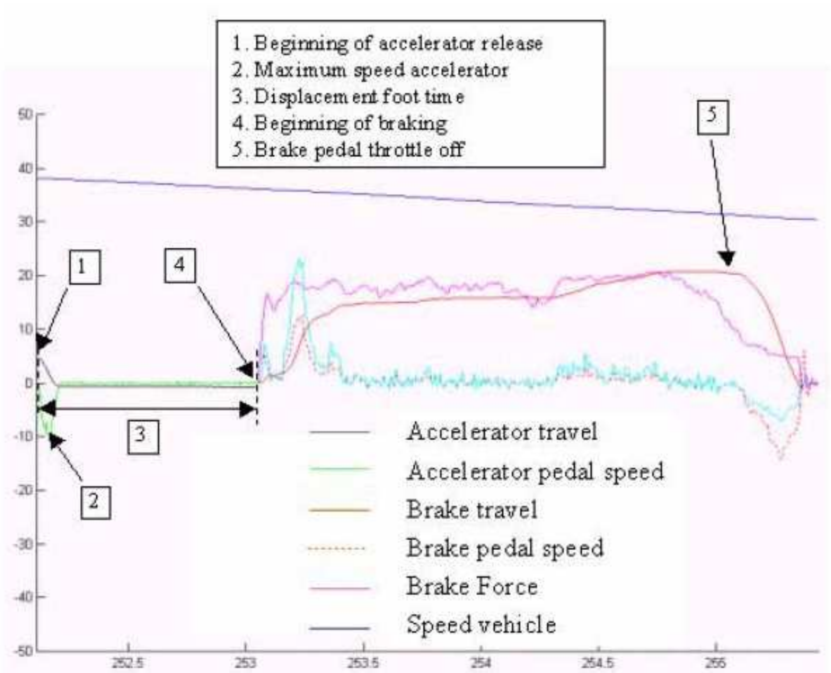


Figure 4: Example Of Normal Braking Phases (Kassagi, 2003)

1.2. Brake actuator as user interface

Taking into consideration the braking phases, the brake actuator is the main user interface the drivers use. Within normal vehicle, it is the responsible of both actions and feedbacks from/to the driver. Basically:

- **Input**:
    - main brake actuator (e.g. pedal);
    - service brake (e.g. handbrake lever, electronic button or lever, service brake pedal).

- **Output**:
  - pedal brake feeling;
  - user' perception of vehicle deceleration;
  - brake rear vehicle lights (they warn other drivers about vehicle deceleration);
  - service brake instrument panel warning light;
  - malfunctioning instrument panel warning lights (i.e. low fluid level, EBD failure, brake pad consumption, ABS failure);
  - ADAS dashboard HMI (e.g. ACC, Hill Holder, etc.).

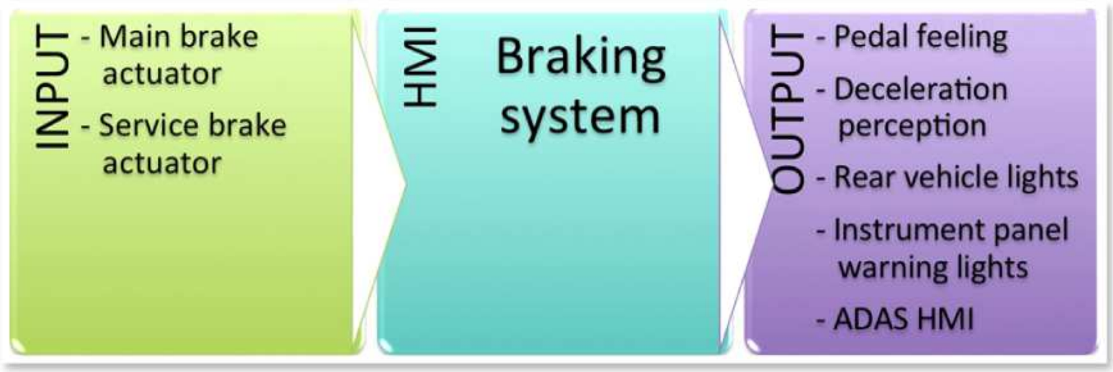


Figure 5: Braking System HMI Input-Output

1.3. Brake force actuation: general movement-force description

The pedal characteristic and feeling the driver perceives during a braking process is given by the force on pedal travel characteristic.

For actuating the pedal a certain response force is required that is basically characterized by preload and friction within the system. During shorter pedal travels, no significant increase of the force can be noticed. This can be explained by the free travels within the system; alternatively, a deceleration is already caused after overriding the free travels without an increase of the force according to the layout. The results is also evident the presentation of the decelerations by pedal force. This function, which is also called the "springer functions" has a positive effect on the subjective perception of the responsiveness.

After this initial step, the pedal force is generated throughout the pedal travel and an incline of the curve can be noticed after the intervention of the Electronic Brake Force Distribution (EBD). At a certain value, the control point of the brake booster is reached and thus the maximum brake force support is reached. Beyond this point the driver perceived a mechanical stop. For this reason, a suitable dimensioning of the brake system guarantees that the control point does not have to be exceeded even in cases of full braking.

By actuating the brake pedal, a braking pressure is built up within the brake system that develops a slightly progressively throughout the pedal travel after overriding the free travel due to nonlinear stiffness. The variable deceleration and pedal force perceived by the driver finally lead to the characteristics in which the influence of the "spring function", the braking force reduction by EBD as well as the influence of the control point can be recognized (Brauer , Bill, 2008).

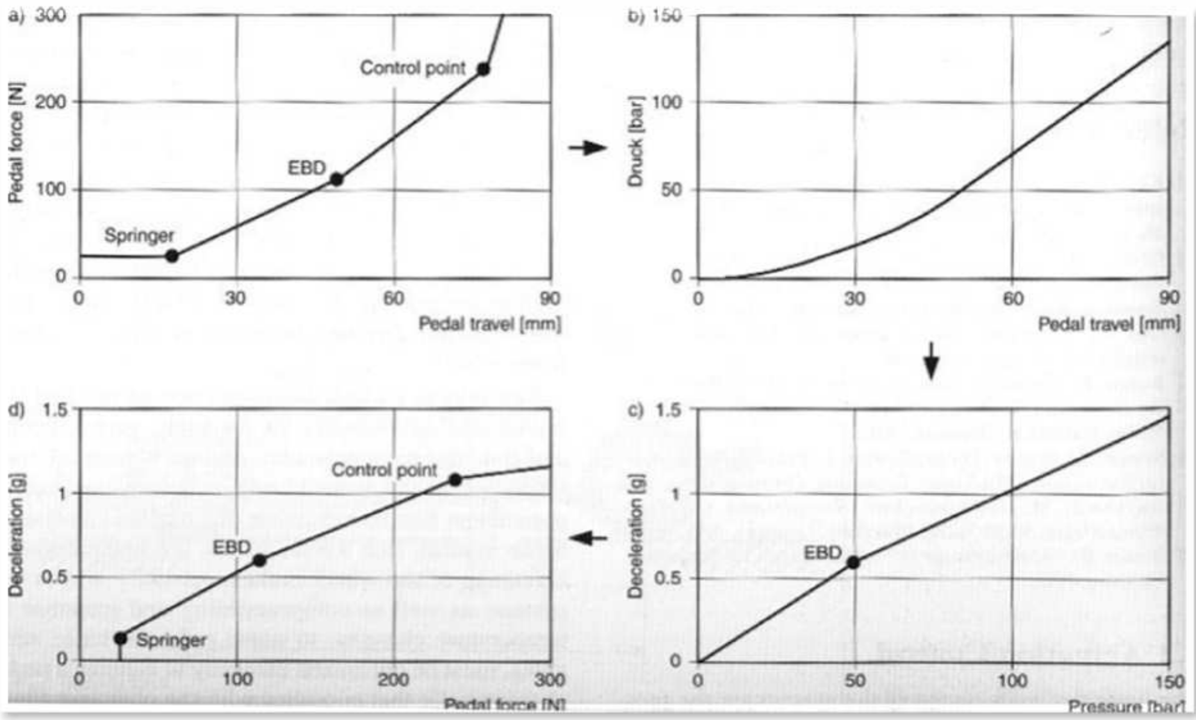


Figure 6: Pedal And Deceleration Characteristics (Brauer , Bill, 2008)

A number of design variables concerning braking response and controllability can be derived from all the characteristics presented above:

- length of travel and minimal braking pressure for certain pedal travel;
- the initial step;
- response force;
- incline of pedal force development throughout pedal travel and deceleration.

A complex and high-precision optimization of all the parameters is necessary for attaining an actuating feeling the customer perceives as a particular quality feature. For instance even moderate increases of the response force can lead to the fact that the brake is subjectively perceived as being dull. Alternatively, it becomes evident that a short pedal travel is subjectively perceived as being favourable when the pedal forces are equal (Breuer , Bill, 2008). Brake force measurement and evaluation it is strictly related to type of car and its braking system. Applied forces and pedal travel could differ a lot between different type of cars and technologies involved in the braking system. The effectiveness of the force applied in traditional system is mainly dependent on the pedal ratio of the brake. The effective force in traditional brake systems with pedal lever and push-rod can be calculated using the following equation (Oshiro 2010):

*Effective Force = Force Applied * Pedal Ratio*

Research studies reported there is no consistent difference in decelerations once the pressure exceeds 10-15 kgs. That is presumably due to ABS activation, so additional pressure does not increase deceleration. An optimal deceleration is achieved through fast and firm pressure on brake

pedal of at least 10-15 kgs and the pressure on the pedal must be sustained until the vehicle has come to a complete stop (Harsha et al., 2008). Although it has been established that some 50% of car drivers do not depress the brake pedal hard enough in emergency braking situations (Youshida, 1998) and that the most subjects apply too little force to the brake pedal and fail to maintain constantly high pressure on it (Kinkner et al., 1997).
Inexperienced drivers tend in critical situation to relax pressure on the brake pedal between 0,1s and 0,2s after initiation of breaking and only start to reapply pressure when the hazard is dangerous close (Zomotor, 1987).
On the other hand, significant differences can be observed between touring cars and sport cars: touring cars have usually longer pedal travel (upper than 72 mm) and less required force (i.e. between 10 and 20 kgs) than sport cars. Typically sport cars require a large braking pressure (i.e. between 18 and 25 kgs) and the brake pedal has a very short travel (i.e. between 34 and 62 mm). In extreme cases, for instance in sigle-seater race vehicles, the brake pedal needed to take a about 2000 N force (about 204 kg), but needed to also be lightweight for design points. In such a cases, the pedal design is even more important, especially at the contact point from the foot of the driver, because that is where the most force would be applied (Scheitlin, 2011).

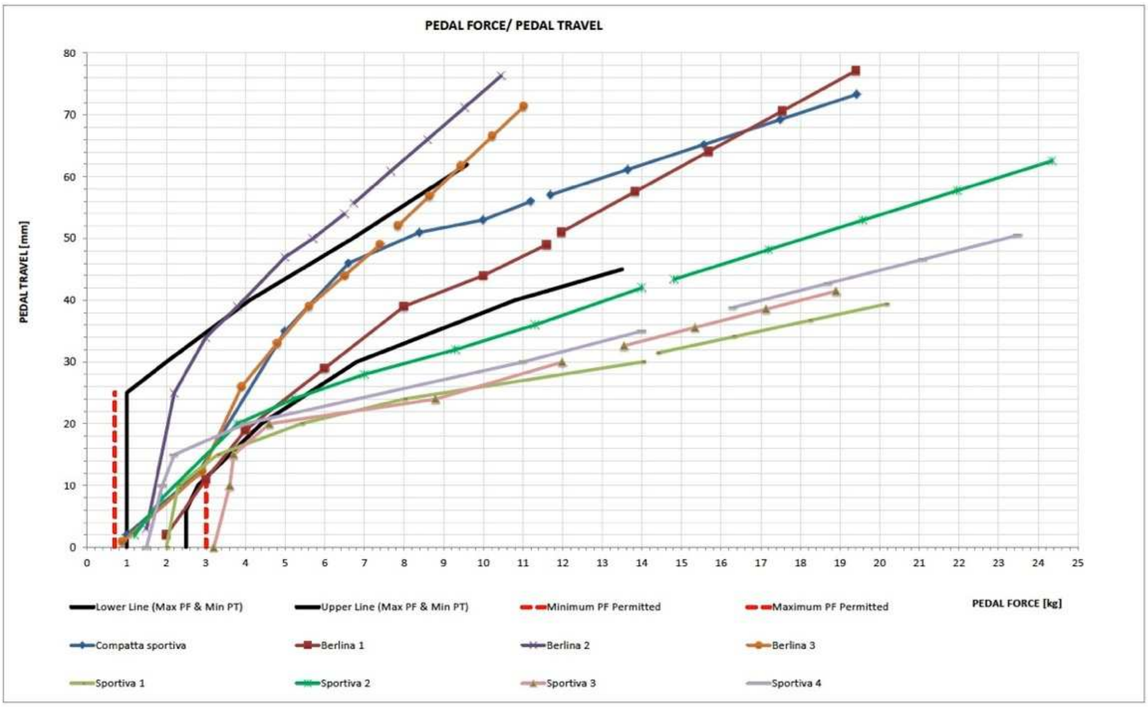


Figure 7: Example Of Pedal Force And Pedal Travel Described By Type Of Vehicle (Brembo 2012)

The USA 2001 AASHTO Green Book suggests a deceleration of 3.4 m/s^2 as comfortable for the majority of drivers. Some differences in values can be noticed in European national standards In (e.g. the Danish Road Standards and Guidelines for rural roads suggests 2,0 m/s^2 as comfortable deceleration).

2. Brake pedal feeling and impact factors

2.1. Introduction on brake feeling

Brake pedal feeling is the physical sensation and perception experienced by the car drivers during braking actions. It is typically referred to the foot sensation touching and acting on the brake pedal following leg-foot movement. As braking is a mechanical process first involving vehicle deceleration, brake pedal feeling results in a complex and structured phenomenon and physical sensation experienced as long as pedal is actuated by driver. Thus brake pedal feeling is first of all strictly related to the applied force and the experienced pedal travel. Other mechanical, physical, dynamics and external situation related factors impact on the perceived brake pedal feeling.

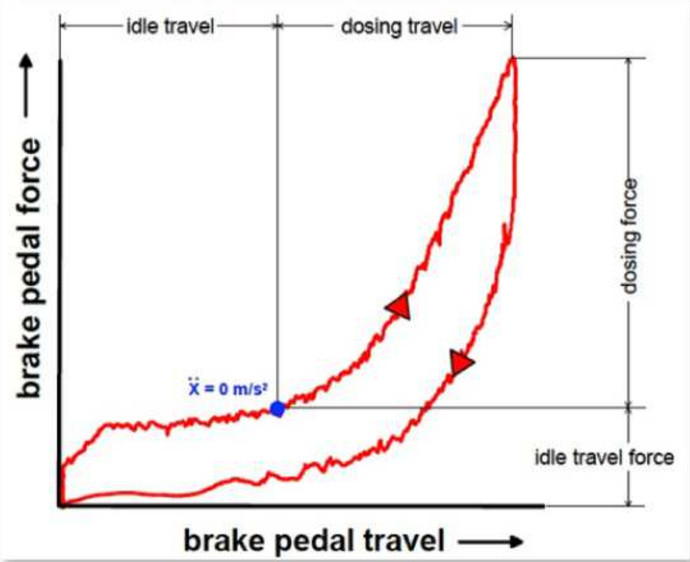


Figure 8: Regions of the usual brake pedal characteristic (Bill et al., 1999)

2.2. Impact factors on brake feeling

Desired brake pedal feeling design is assuming even more importance as electro-hydraulic and fully electronic brake systems are currently under study and development by OEMs. Since the electronic systems use electrical signals to transmit brake pedal movement to the brakes, these systems use a brake pedal simulator to provide feel and feedback to user as a traditional brake pedal. Vehicle and brake designers are not constrained by the physics of the brake system in designing the brake pedal feel and in theory they will be able to design exactly the most effective and efficient feeling even more the most desired one by drivers. It is conceivable that individual drivers may be able to customize the brake pedal feel of their vehicles and thus every driver will have their ideal brake pedal feel (Cerilles, 2005).

About vehicle braking systems, the crucial user interface is the brake pedal as it is both input and output interface. The pedal feel provides feedback to the driver about the performed braking manoeuvre and the state of the braking system. The pedal characteristics can be influenced by changes to the brake system and to the overall actuation complex. This variability is mainly exploited as part of style of the vehicle marque or model. The key parameters brake-related determine pedal feel can be listed as follow (Breuer, Bill, 2008):

- pedal response force;
- pedal idle travel;
- braking two-stages effect (also called damping or jump-in factor);
- braking boost (deceleration/pedal force);
- hysteresis;
- pedal travel;
- pedal travel and pedal force at the run out point (ideally corresponds to maximum deceleration);
- increase in pedal travel and pedal force on fading;
- response time;
- release time.

When braking, driver is integrated as a controller in the closed-loop control system within the vehicle control line. Following research hypothesis and driving experiments, the dependence of brake pedal parameters from braking situations has been shown. For instance, in modern vehicle electronically equipped, brake pedal interface becomes even more important in some situations (e.g. hard braking occurrences, ABS activations and pedal vibration).
If the positive subjective brake pedal feel has a positive influence on the operating reliability of the driver, performing of emergency braking and speed adapting braking are also influenced.
While brake pedal characteristic curves can be judged with the usual experimental means of vehicle engineering, the consideration of brake pedal feel requires also methods from ergonomic and human factor sciences.
Required braking force and feeling can be made dependent on numerous supplementary parameters. In particular the situation of the driver in his current state (e.g. body size, height, muscle-skeletal condition, etc.) can be considered in addition to the actual state of vehicle dynamics and pedal-related parameters previously listed. Also the driver's gender, driving style and behaviour can impact on the perceived feeling and potentially on the desired one. Last but not least, external situation as environment and driving cases will definitely impact on brake feeling (Bill et al., 1999).

Pedal and braking system related aspects	**Travel** Idle travel Pedal transmission Clearance System volume usage Increasing of travel on fading **Force** Pedal transmission Booster amplification Required applying force Pedal response force Increasing of force on fading **Damping (also called Jump-in) and hysteresis** Two-stages effect Component-friction Booster hysteresis Booster dynamics Throttling if booster pneumatic ABS valve throttling Line cross section
Vehicle deceleration	Friction brake pad / disc Friction tire / street surface State of the vehicle Gradient of the street
Vehicle parameters	Geometry and positions of pedal, seat, steering wheel Special vehicle behaviour Vehicle challenge characteristic Vehicle type
Driver	Body size Condition and motivation Power and capacity Demands Gender Driving style
Environment	Weather Street course Road surface and type Traffic density

Table 1: Detailed variables influencing the brake pedal feel (based on Bill et al, 1999).

As reported, several factors impact on the user perceived brake pedal feeling including both the ones that could be managed by vehicle designers and the external situation-related factors that cannot be managed at vehicle designing.

For instance, regarding emergency braking and dosed comfort braking, jump-in and idle travel are important parameters for controlling the braking system. The jump-in, as specific feature of pneumatic brake booster, is performed as a brake pressure jump at the end of the idle travel. With this pressure offset the clearance of can be surmounted and a defined small vehicle deceleration will be performed with very low brake pedal force, which gives the driver a positive feedback in brake pedal feel when starting to brake. With missing jump-in, the brake pedal is felt as "blunt" as vehicles without braking force enhancement (Bill et al., 1999).

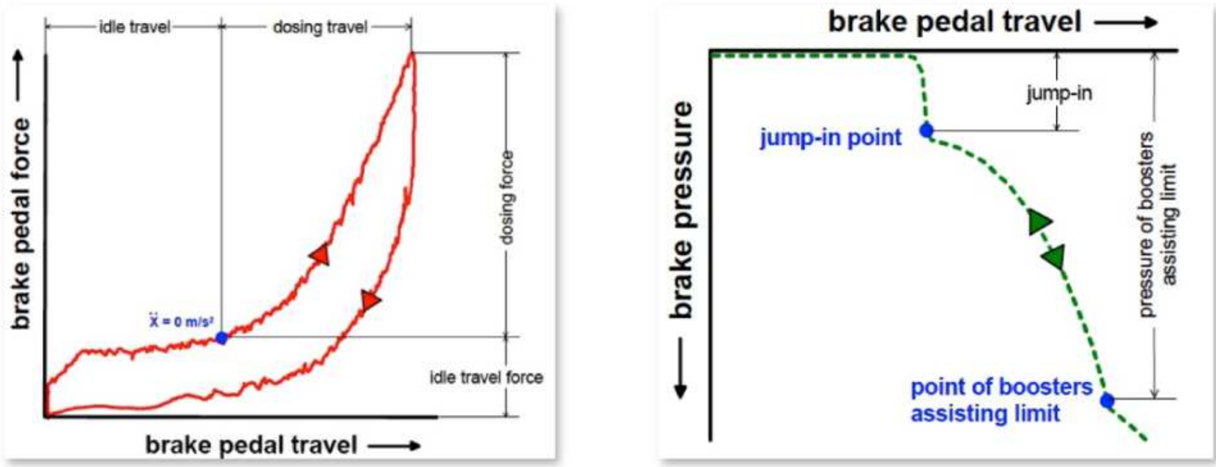


Figure 9: Brake Pressure, Force, Jump-In And Pedal Travel

According to very relevant experimental tests performed by Bill et al. (1999) in order to investigate brake pedal under real road conditions in view of oncoming of brake by wire systems, the variations of individual brake pedal parameters seem to be difficult to recognize clearly for most drivers. For instance, the isolation of the force and travel information at the brake pedal in combination with retroactive vehicle deceleration is difficult to recognize especially for inexperienced drivers.

Some of the above listed parameters are impacting on the overall brake pedal feeling perceived by users and also on vehicle braking performance (i.e. braking distances) but they are not related to pedal design or to the braking system itself. Typically external factors as road type, weather conditions or maintenance aspects impact on performances. These aspect could be foreseen in use case definition but cannot be set as fixed conditions for technology development and future product on market. Thus it also important to consider them as relevant variables.

Information about the significance of the above parameters for braking distance is based on literature. The most relevant findings of those studies are cited below (Greibe, 2007).

2.3. Research performed by Renault about factors impacting on brake feeling

Renault car manufacturer performed a relevant research (Dairou, Priez, 2003) aiming at defining the user model related to the perception of brake pedal feeling and to fix the impact factors of pedal technical parameters.

To sum up the research, Renault first defines "laws" pedal feeling is based on, both user action and physical related defining technical pedal characteristics.
Assuming that brake pedal feeling is strictly related to applied effort, pedal stroke (i.e. travel) and vehicle deceleration, Renault identified 11 primary factors that could be modified and set in order to adjust brake pedal feeling laws.

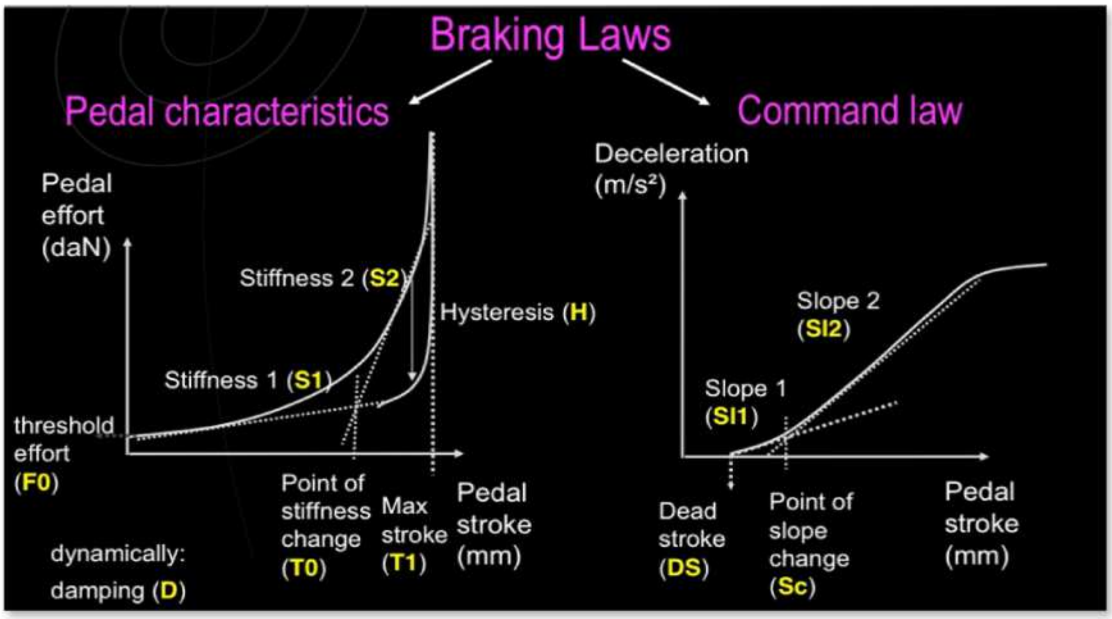


Figure 10: Parameters identified by Renault to adjust brake feeling laws (Dairou, 2003).

Detailed user tests have then been carried out by Renault in order to estimate how much each factor could impact on brake feeling and to define the driver model about perception. Through prototype equipped vehicle and pedal simulator, it was possible to test different braking configuration in order to assess the impact factor and the correlation between the 11 variables identified. In order to limit the test to most relevant characteristics and ensure controllability of variables, the Design of Experiment was defined involving a subset of 7 pedal attributes:

- travel;
- idle travel;
- effort;
- responsiveness;
- deceleration perceived;
- ease of balance (i.e. ease of modulation);
- graduality of braking (i.e. controllability).

Renault's test intent was to assess the influence of the parameters of the braking on the sensation of the driver, both as negative and positive effect. That allowed researcher to carried out a predicting model derived by coefficients resulted from the study.
The correlation between predicted sensation and observed sensory ratings results as follows.

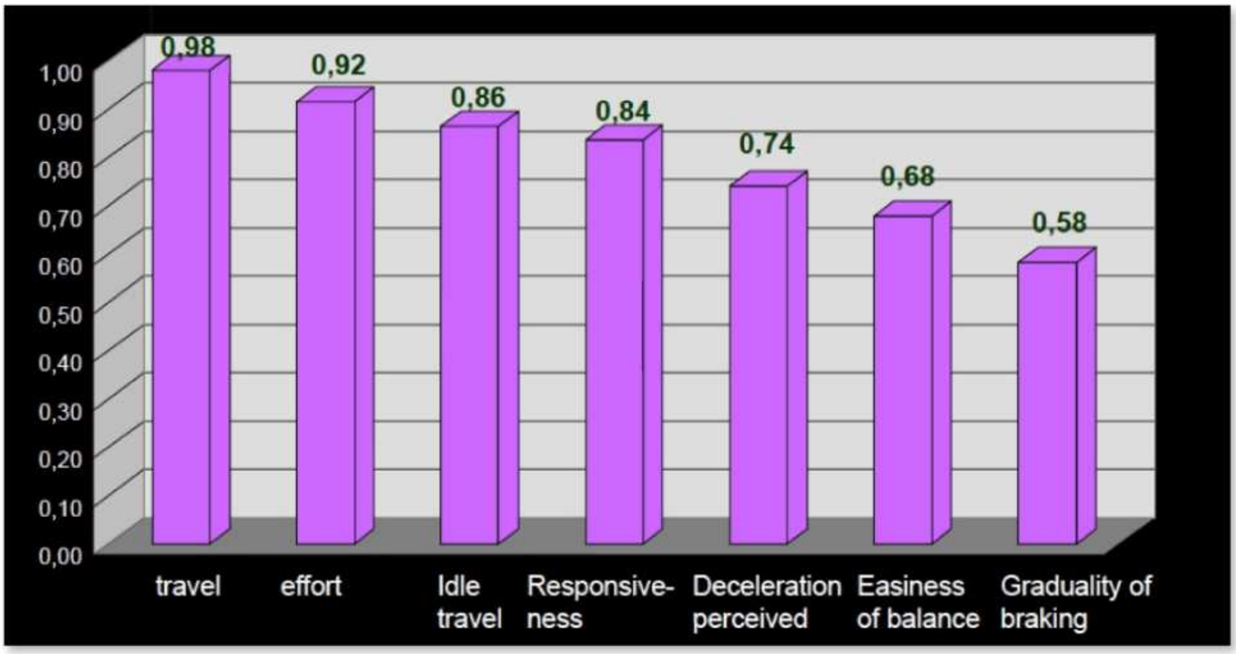


Figure 11: Correlation among predicted sensation and sensory ratings (Renault, Dairou, 2003)

The outcomes of the research allowed human factor specialists and vehicle designers to consider each pedal characteristic also from the point of view of its impact on brake feeling as a valid predictive model has been defined.

3. Pedal feeling design

3.1. High-level requirements

Typical "x-by-wire" systems comprise of redundant sensors, actuators, microprocessors, and communication channels for fault tolerance in order to interprets driver's input and executes the command to produce desired vehicle behavior typically via a microprocessor-based control systems. No mechanical or hydraulic connection between driver's input interface (e.g. pedals) and vehicle system are present. Drive by wire systems are able to incorporate multi-functionality in a single system allowing cost effective advanced features also in touring passenger cars (Sohel, Bing, 2006). Brake by wire offer new chances for optimized integration of driver in the vehicle control loop in the design of the actuation device. In theory, the actuator device could be adapted individually and dynamically to the combinations of the overall system user-vehicle-environment driving situation (Breuer, Bill, 2008).

The process of achieving high customer satisfaction in brake pedal feeling begins with correctly defining customer requirements and translating those requirements to matching design attributes. For example, a customer requirement that the brake pedal needs to feel "predictable" may be translated by the design engineer into a linear brake pedal feel. Then those design attributes must be further translated into well-defined product specifications and manufacturing process specifications so that manufacturing can build the product according to the original design intent (Cerilles, 2005).

Five distinct classifications could be reported about brake by wire based on actuation features (Sohel, Bing, 2006):

- Electro-hydraulic brake by wire systems (EHB);
- Electro-mechanical brake by wire systems (EMB);
- Electro-magnetic or electric eddy current brake by wire system. Frictionless braking system (e.g. Telma retarder system integrated with axle or driveline);
- Regenerative braking via electric generator;
- Hybrid brake by wire system with more than one actuator types indicated above.

Brake by wire technology could ensure several benefits to the overall automotive system both for passenger cars and heavy vehicles. It is anticipated that opportunities deriving from new technology large scale adoption will impact on safety, both active and passive for drivers and car passengers, but also for safety in general transportation system. Adapt brake feeling to driving situations and provide drivers suitable feedbacks or warnings, it is anticipated that could lead to a reduction of chance of incidents and accidents in addition to a potential improvement of braking performance and reduction of braking distance in several driving conditions and contexts. Brake by wire technology could also impact on environment aspects and in general energy efficiency of vehicles.

Brake By Wire potential benefits
Enhance safety
Improved braking performance (general and situation adapted)
Improved energy efficiency
Improved ergonomics
Low impact on environment
Tuneable brake feeling
Reduction of NVH and driver comfort
Better fault detection and warning
Easy maintenance
Integration with ADAS (stability and guidance)

Table 2: Brake by wire Potential Benefits

In the following table, high-level conceptual requirements for brake by wire design, development and deployment are listed. They summary aspects to be considered designing the system in order to meet as much as possible expected benefits and enhance the impact of them on the overall transportation system.

Active safety	- Slip control, speed control, drive stability and driver-assistance systems. - Wheel selective actuation (intended and controllable). - High system dynamics(reduction of delay times) for the shortening of braking distances and vehicle stabilization (apply and release). - Lightweight construction: wheel sprung mass, reduction of vehicle mass. - Optimized and situation-dependent configurable characteristic of the actuation device (coupling of the driver)
Passive safety	- Increase of passenger protection (crash compatibility of pedal box) - Limitation of critical space requirements
Signals	- Possibilities for external system interventions. - Parallel working command sources (driver's signal, signals from vehicle controllers). - Transparent flow of information (interlinking). - Safe and continuously working error diagnosis and warning for drivers.
Energy	- Low power demand of the braking system. - Minimal residual brake torques. - Possibility of brake energy recuperation.
Material, Environment, Costs	- Avoidance of problematic substance, recycling friendliness. - Enhancing mechanical and thermal reliability and long-term quality. - Assembly-, service-, and repair-friendliness; components with little or no maintenance. - Costs, assembly, maintenance, economic efficiency.

Table 3: Future Braking Requirements And Possible Benefits (Source: Breuer, Bill, 2008)

Future braking system represents the basis for ADAS based on vehicle-internal signals. Their potential also includes optimal use of physical possibilities, the supply of additional safety functions, easy and environment compatible maintenance of braking system as well as improved ergonomic driver interface. In traditional systems, users perceived direct connection between actuator (i.e. brake pedal) and deceleration. Future braking systems have also access to external control systems (e.g. stability control, ACC, etc.). These two sources of longitudinal regulation could arise in "conflict" for the function and control allocation. The energetic decoupling of the actuation device and the transmission device leads to a power braking system and can offer so far unknown degrees of freedom designing HMI. Thus, an uncertainty or irritation of the driver during the brake actuation of the ADAS is avoidable and a specific haptic information is possible. The application of alternative operational controls is easily feasible and a crash-compatible construction can be accomplished (Breuer, Bill, 2008).

3.2. General aspects

In a brake by wire system, braking intention should be transferred from the pedal to the actuator. Braking should be felt back to the driver using the pedal. Usually power assist function should be in action to assist the driver for controlling the pedal. If bilateral system is used above functionalities can be easily incorporated to brake by wire system. Power assist function is possible with power scaling in bilateral control (Harsha et al., 2008).
In brake by wire system control units, which have to detect the drivers input, calculate the corresponding brake effect and actuate the braking system. That imply also the compensation of latency periods. The gradient of deceleration after time gap is similar to that one of conventional braking systems. So if faster bus architecture is used, the braking dynamics of brake by wire systems become sustainably better (Kircher, Sendler, 2012).

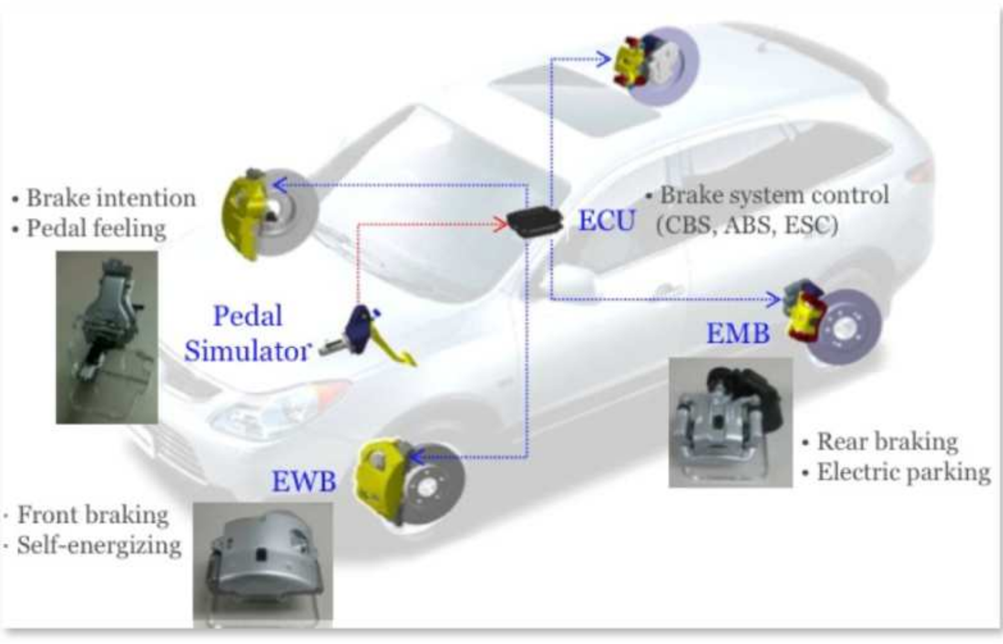


Figure 12: Example of brake by wire architecture (Cheon et al., 2010)

Main system architecture components:

- Vehicle networks (e.g. CAN, TT, Power supply);
- Electronic Control Unites and Vehicle Control Systems;
- Brake control Units;
- Sensors (e.g. pedal strokes, driving situation related, ADAS, etc.);
- HMI for input (i.e. brake pedal, service actuator, other input as selectors);
- HMI for output (i.e. brake pedal feedback, instrument panel and GUI, internal and external warnings).

3.3. Designing example

The following chart and diagrams show as example the aspects considered in a research programme, called Challenge X, that had aimed at design and develop a regenerative brake pedal concept for ME 450 vehicle (Pan, 2007).
The F.A.S.T. diagrams shows the main aspects to be ensured and the derived parameters researchers considered to be set.

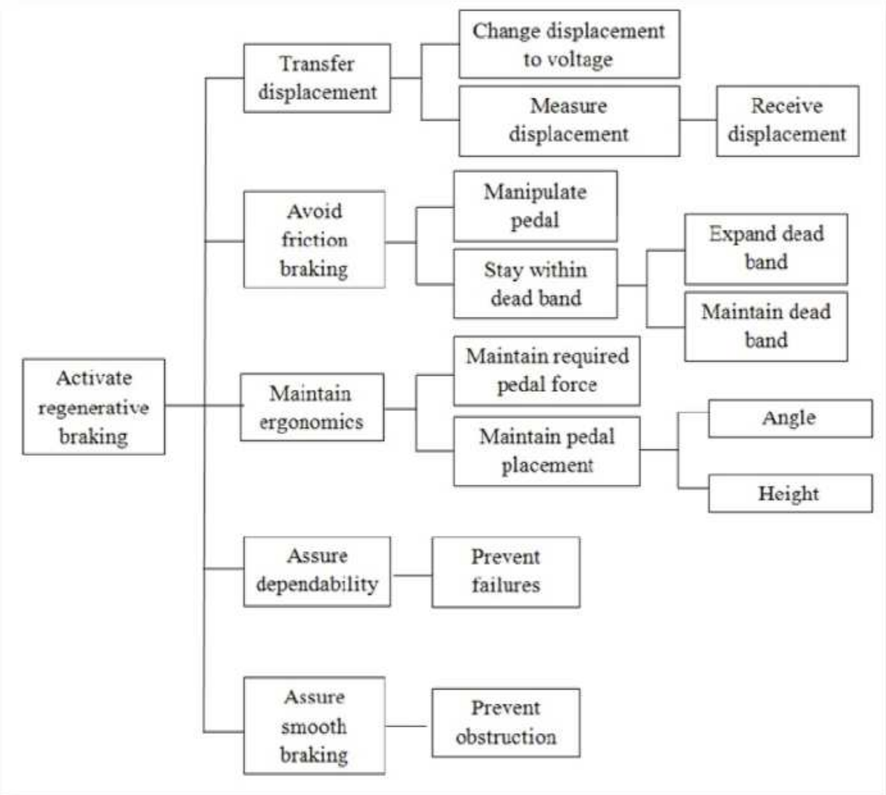
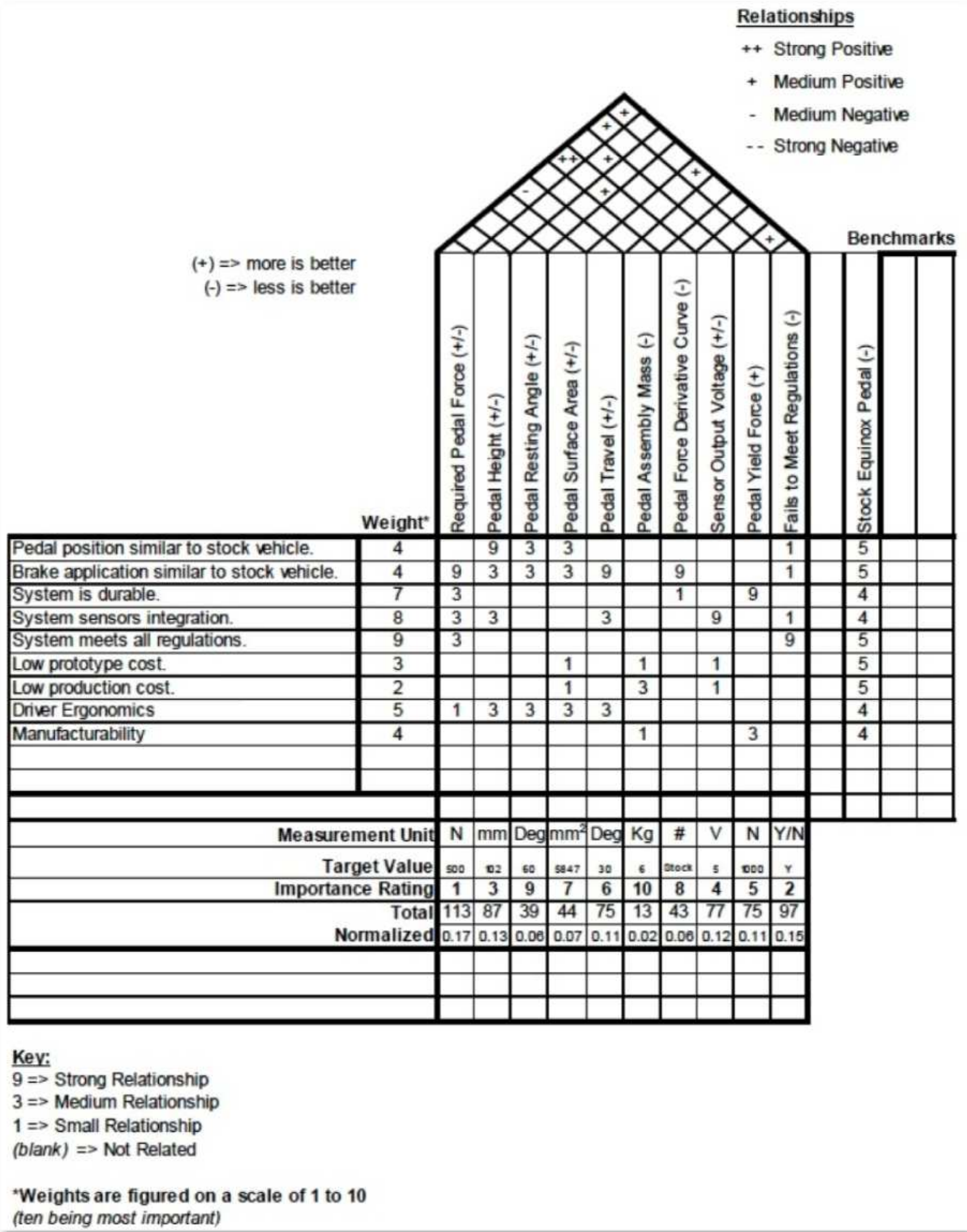


Figure 13: Example Of Function-Analysis-System-Technique Diagram For Brake Design (Pan, 2007)

The following diagram reports as example the values considered for pedal development according to the selection criteria defined by researchers in order to decide which technical architecture adopt for the concept further development (i.e. mount sensor to pedal and back bracket with a four-bar linkage).



	Weight*	Required Pedal Force (+/-)	Pedal Height (+/-)	Pedal Resting Angle (+/-)	Pedal Surface Area (+/-)	Pedal Travel (+/-)	Pedal Assembly Mass (-)	Pedal Force Derivative Curve (-)	Sensor Output Voltage (+/-)	Pedal Yield Force (+)	Fails to Meet Regulations (-)		Stock Equinox Pedal (-)		
Pedal position similar to stock vehicle.	4		9	3	3						1		5		
Brake application similar to stock vehicle.	4	9	3	3	3	9		9			1		5		
System is durable.	7	3						1		9			4		
System sensors integration.	8	3	3			3			9		1		4		
System meets all regulations.	9	3									9		5		
Low prototype cost.	3				1		1		1				5		
Low production cost.	2				1		3		1				5		
Driver Ergonomics	5	1	3	3	3	3							4		
Manufacturability	4						1			3			4		
Measurement Unit		N	mm	Deg	mm^2	Deg	Kg	#	V	N	Y/N				
Target Value		500	102	60	5847	30	6	Stock	5	1000	Y				
Importance Rating		1	3	9	7	6	10	8	4	5	2				
Total		113	87	39	44	75	13	43	77	75	97				
Normalized		0.17	0.13	0.06	0.07	0.11	0.02	0.06	0.12	0.11	0.15				

Figure 14: Example Of Quality-Function-Deployment Diagram For Brake Design (Pan, 2007)

The following table shows the engineering specifications for brake pedal design defined in the Challenge X programme (Pan, 2007) taken from the customer requirements after discussing with designers.

Specification	Measurement Unit	Target Value	Importance Rating
Required Pedal Force (-)	N	< 500	1
Pedal Height (+/-)	mm	102	3
Pedal Resting Angle (+/-)	degrees	60	9
Pedal Surface Area (+/-)	mm^2	5847	7
Pedal Travel (+/-)	degrees	30	6
Pedal Assembly Mass (-)	kg	6	10
Pedal Force Derivative Curve (-)	#	Stock	8
Sensor Output Voltage (+/-)	V	5	4
Pedal Yield Force (+)	N	1500	5
Fails to Meet Regulations (-)	Y/N	Y	2

Table 4: Example Of Pedal Design Engineering Specification: Active Pedal Feeling Design Parameters

Brake pedal feedback can be seen as passive pedal, i.e. mostly mechanical, or active pedal, i.e. able to provide dynamic and tuneable feedbacks to users.
There is no problem with weak feedback at "zero" zones since there is only one direction of pedal depression and the brake pedal is naturally weakest at its "zero" position. For instance, a mechanical spring or a spring and dumper set could be used.
The active feedback on the brake can successively suppress negative influence of deceleration cues absence in case of driving simulators. Drivers of car simulators are often disappointed by inadequate car reaction in braking situation. In fact, the physical model can correctly compute all this processes but drivers cannot control the braking in the same way as they would in the real car. The reason is that they cannot obtain precise feedback from the car behaviour they are very sensitive to. The driver having no realistic feedback of a real progress of deceleration usually brakes harder than in real driving conditions. In order to face this issue in driving simulator is usually present an auditory warning like a slick sound, but this is not natural for common driving and drivers usually do not evaluate it correctly. Progressive resistance of the pedal and ABS pulses are able to improve the situation significantly (Bouchner, 2011).
In order to set up a brake pedal simulator, or an electro actuator deployed for brake by wire system, it is necessary to represent in the unit the force/travel characteristic of the brake pedal that is required by the customer, human factor specialists and OEM developers. That also allowed designers to size the pedal feeling.
Trade-offs and the pedal feel over deceleration could be adjusted by software. Also required brake pressure and associated deceleration to brake pedal travel can be command by software.
Basing on research studies, further development of the brake actuation complex will be aimed at low idle travel, low response forces and high two-stage effect to ensure that the braking system provides as direct response as possible. Further objective includes high levels of boost and short pedal travel to improve comfort (Breuer, Bill, 2008).
As described in previous section, a wide range of characteristics and influences impact on brake pedal feel. With the destination of a stronger numeric approach to the objectivity of brake pedal feeling depending in the respective driver expectation and the vehicle type, investigations were carried out by establishing a brake feel index (Ebert, Kaatz, 1994). However, these approaches were concentrated on few specific motor vehicle types and therefore no universal references can be given. Currently through equipped vehicle, there is the chance to modify the brake pedal

characteristics and vehicle deceleration in wide rage for a systematic investigation of brake pedal feel in real driving situations in addition to numerical solution strategies (Bill et al., 1999).

Jump-in and idle pedal travel

Researches and experimental tests demonstrate and measure the impact of some parameters on pedal feeling (i.e. impact on the overall perception of pedal travel and pedal force). The following figures show the results from a test carried out by Bill (1999) through jump-in and idle pedal travel variation respectively.

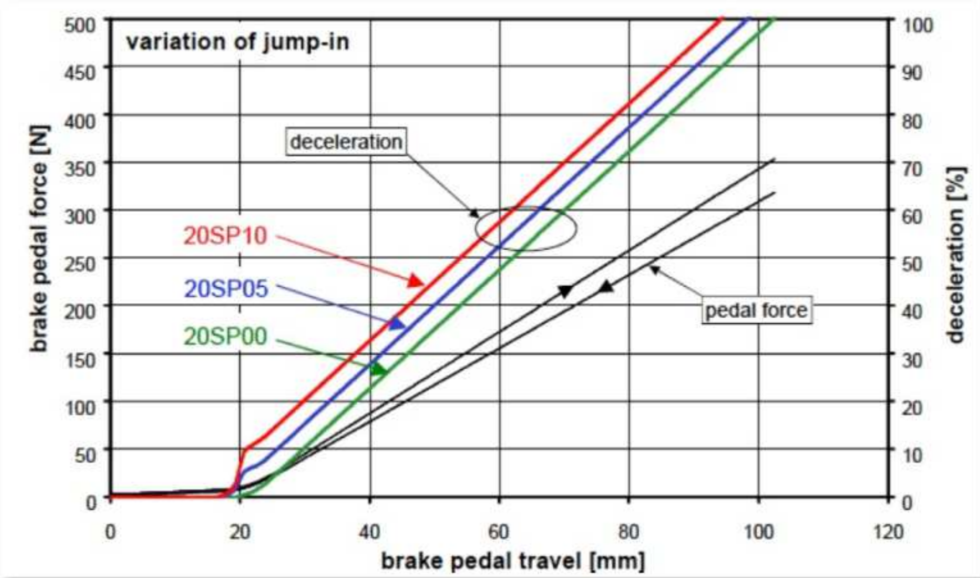


Figure 15: Derived curves by jump-in variation 0%, 5%, 10% (Bill et al., 1999).

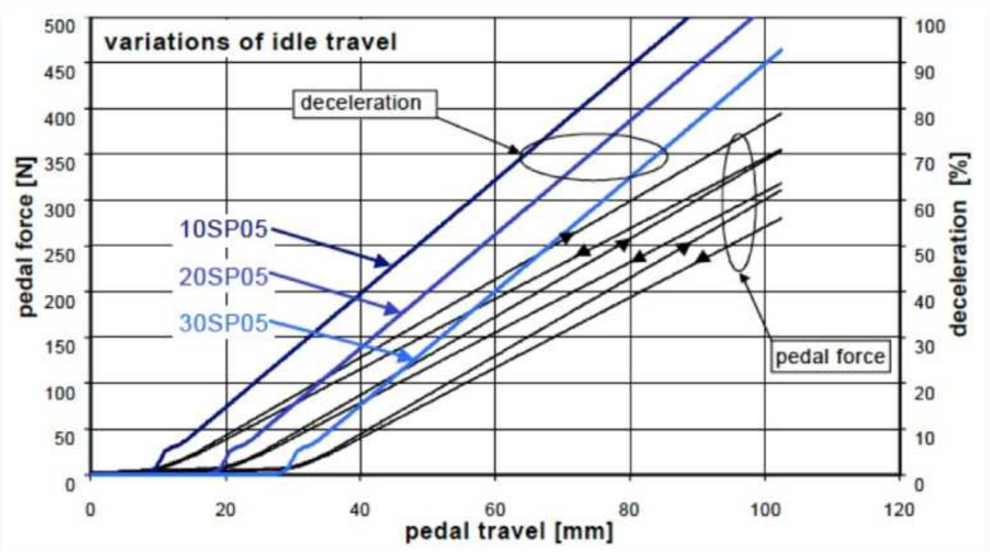


Figure 16: Derived curves by idle pedal travel variation 10mm, 20mm, 30mm (Bill et al., 1999).

About judgement of the pedal feeling in the research study carried out by Bill (1999), different users' expectations seem to exist with respect to the brake pedal during strong, average and weak decelerations. Evaluations deliver situation-dependant judgements of brake pedal feeling.
For deceleration > 20% (respect regular adaptation braking) a perceived stronger jump-in is favoured, but in case of parking and decelerations <= 20% a perceived strong jump-in has a disturbing effect. In case of deceleration > 20% a short perceived idle travel was preferred by the users in agreement with the goal of making reaction time of brake system as short as possible.
On the other hand, an increasingly perceived longer pedal idle travel way is favoured during smaller deceleration, which becomes clear during judgement on deceleration <= 20% and braking during parking maneuverers.
In the presented study, differences are small in the general assessment of the pedal feeling. For experimental investigations of the pedal force and pedal travel the parameter grading must be adapted corresponding to the ability of drivers' sense of touch. However a mutual compensation of pedal force and pedal travel with respect to the brake pedal feeling is possible (Bill, 1999).

3.4. Situation adapted properties - Use cases and users' expectations

The sense of touch between driver and vehicle is of great significance for a subjective opinion on the part of the driver and for the driver safety when controlling the car's deceleration. Active safety is directly influenced by the controllability of the brake system actuation and has an equally important influence on driving safety. In brake by wire system ideal opportunities for the development of a newly oriented brake pedal are made possible. These possibilities cover anthropometrical, physiological, movement, information and safety aspects.
Consequently, with brake by wire systems the chance for the individual and driving-situation-dependant adjustment of the brake pedal is given. With respect to ergonomics and active safety already the brake pedal design and characteristic was repeatedly investigated in the past with view to wheel locking and then to ABS.

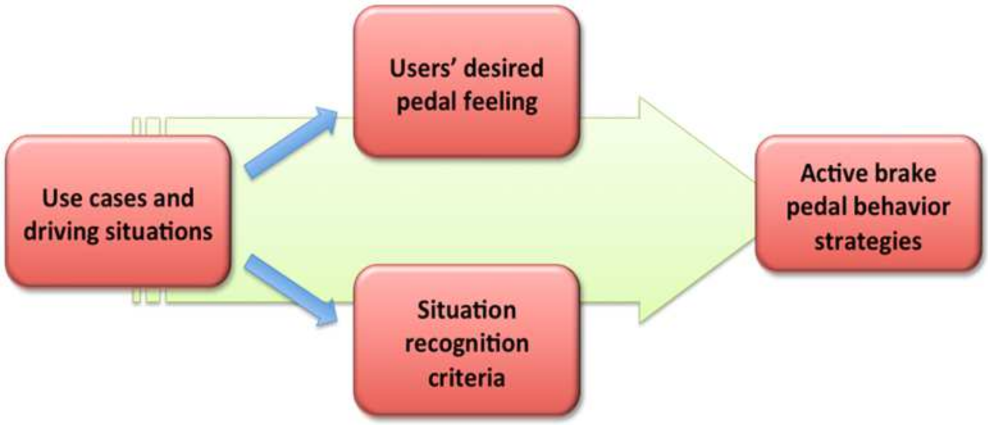


Figure 17: Active Brake Pedal Behaviour Strategy Outline

Figure 18: Driving Use Cases Concerning Braking

Experimental results from user tests confirm the need of a driver dependant adaptive behaviour of the brake pedal characteristic and of a "smart" brake pedal for future brake by wire system. That could also fit theoretical considerations for the enhancement of active safety as significant improvement of the drivers condition during braking and an increase of the braking stability of the vehicle seem possible. Furthermore, anthropometrical and physiological considerations lead to a "personalized brake pedal" as, with the view of brake by wire systems, a driver individual and braking situation dependant brake pedal characteristic is possible in principle (Bill et al., 1999).
To optimize the driver's support, the actual brake situation must be taken into consideration for the design of a concrete behaviour of the actuation device. The following figure shows the desired situation-adapted characteristics of the actuation device as a function of braking manoeuver (Bill, 1998). It is referred to qualitative and functional design of single brake pedal qualities standardized at the adaptation pedal.
The following suggestions represent hypotheses of situation-adapted pedal strategies. Curves and remarks do not represent a fixed technical requirement or specification, but show the what seem to be expressed expectation by users. Every suggestion is referred to a reference pedal braking strategy defined as the better one for type of car and vehicle in traditional braking system**.**

braking maneuver	brake pedal facility					
	force F_P	travel x_P	damping $f(\dot{x}_P)$	hysteresis ΔF_P	amplification dz/dF_P	jump-in Δp (Δz)
adaptation	→	→	→	→	→	→
target	→	→	↘	↘	→	↘
emergency	↘	↓	↓	apply ↓ release ↗	↑	↑
holding (e.g. at a hill)	↘	→	↘	→	↗	↗
legend	→ *normal*	↗ *larger*	↑ *large*	↘ *smaller*	↓ *small*	

Figure 19: Desired situation-adapted properties of the actuation device (Bill et al., 1999)

- **Force/travel characteristic** - Drivers need a convenient force/travel (also called displacement) characteristic of the actuation device for the sensitive and specific dosage of the breaking system. Low actuation forces relieve the driver. The actuation forces must at least have a magnitude large enough to prevent unintentional actuation because the effective vehicle deceleration creates additional mass force acting on the extremities that are involved in the brake actuation. Displacement can be adapt flexibly to available space inside the vehicle. Actuation device without any displacement are not reasonable because only displacement makes damping possible.
- **Damping and hysteresis of the actuation device** - Damping is necessary to avoid a destabilization of the braking process as a result of force/displacement disturbances. Damping is undesirable during emergency braking for the lack of a quick rise of deceleration.
- **Amplification ratio between braking force and actuation force -** The amplification ratio can be adjusted according to individual ergonomic requirements and to driving situation. It must be stressed that the stability of the closed-loop control circuit deriver-vehicle-environment may not be disturbed about actuation force.
- **Jump-in** - In traditional system, jumper is used to automatically generate pressure jump to quickly overcome the pad clearance at the beginning of the brake actuation. In the brake by wire systems, this can be realized very flexibly. The jumper transmits high-breaking system dynamics to the driver and gives a positive feedback. In emergency situations, brake by wire can theoretically raise the pressure jump up to the wheel lock limit; however, for parking the jumper is of no use.

NB: the following figure represent hypotheses of Travel-Forces curves. They derive from suggestions about desired situation-adapted properties. Curves do not represent a fixed technical requirement or specification, but show the concept in charts what seem to be expressed expectation by users.

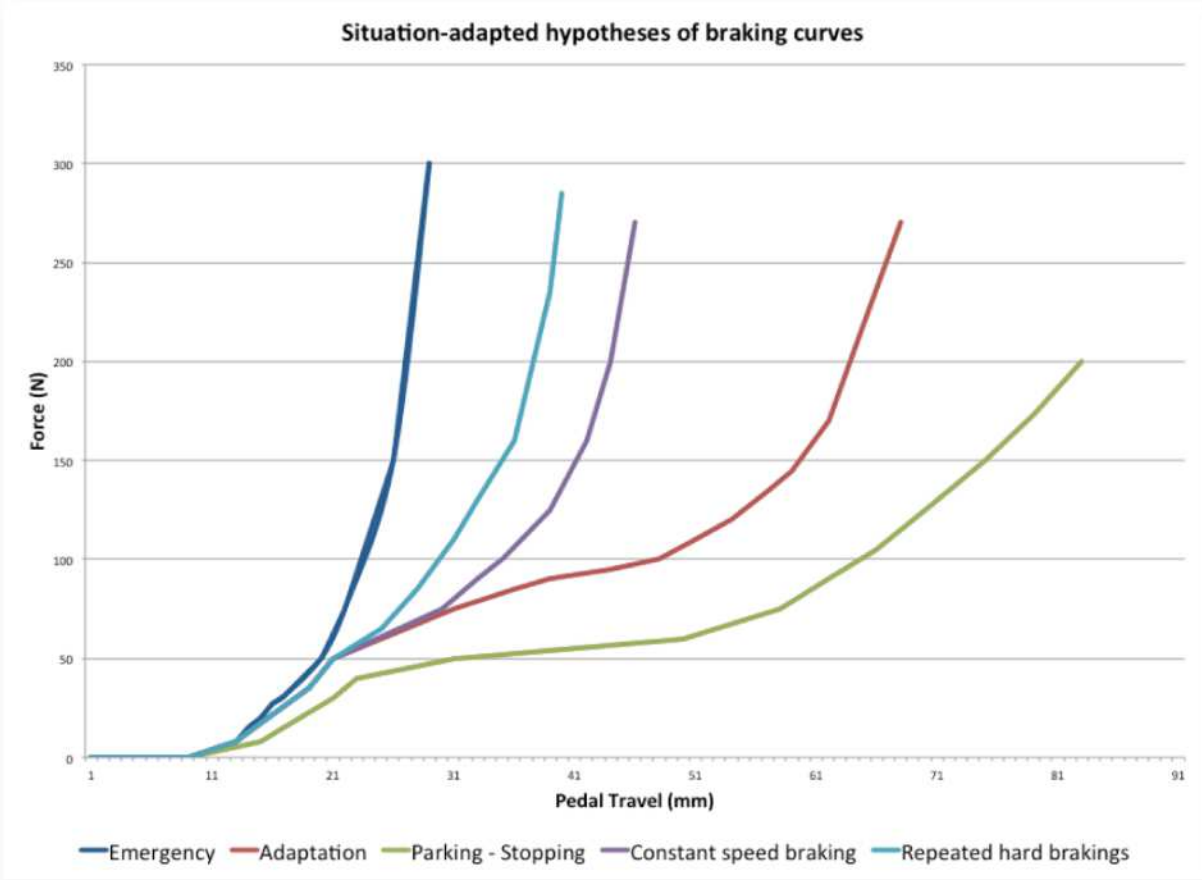


Figure 20: Hypotheses Of Situation-Adapted Braking Curves According To Users' Expectations

3.5. Situation Recognition criteria

Based on what detailed in the paragraph 3.4, a first collection of situation adapted strategies are reported below, jointly with comments on human factor point of view.

3.5.1. Adaptation braking speed reduction while driving or to stop

Adaptation is a regular deceleration as speed reduction in safe condition according to driving behaviour and driving style, will be considered the reference brake feeling. It need to be defined according to car type and users' profile. On human factor point of view, haptic feedback could improve users situation awareness in defined driving situations (e.g. in adaptation of to alert drivers in chance of dangerous situations). User needs to have low workload state or to be very experienced with haptic perception to recognize it correctly. Idle travel needs to be ensured to avoid accidental brake actions.

3.5.2. Target and parking braking

A special trigger (e.g. switch button) could be introduced for use case in order to adapt feeling and force. During braking and in case of parking, normally only very small vehicle decelerations are required. For this reason, the modularity of brake pedal is very important. Low dumping, low hysteresis and especially low level of jump-in is required. The dosability of the braking force will be seriously impaired by a too large jump-in level. However with a large idle travel a phase delay between brake actuation and vehicle deceleration will be produced with a resulting unsafe feeling, which leads to an overreaction of the driver and imprecise breaking behaviour. On human factor point of view, users need typically to stop immediately or to adapt speed for vehicle specific manoeuvring. Response should be immediate. Soft pedal issue should be avoided but high amplification is not required.

3.5.3. Emergency braking

For the optimization of the braking distance during emergency braking, the brake pedal damping has to be minimized together with the smallest possible pedal travel and an enlarged pedal amplification. No feeling of pedal pulsing if ABS is activated. On human factors point of view, it is important to consider the importance of warning provided to users and situation awareness issue. Some users could feel safer if they perceive that braking system is performing at its maximum. Other users could prefer no interference and to delegate the maximum deceleration to braking system.

3.5.4. Constant speed braking (e.g. downhill)

When constant braking is performed the driver needs an high jump-in and a high pedal amplification which leads to low brake pedal forces.
On human factors point of view, users expect to have constant brake performance while action is in progress and to be aware of possible failure or system change in performance.

3.5.5. Repeated hard braking - Similar to emergency braking (e.g. race scenario)

Similar strategies to Emergency braking but repeated and performed intentionally and at expected points. On human factors point of view, it's important to provide driver detailed information about braking status. Improve situation awareness if failure occurs. Drivers should be aware of performance applied.

3.5.6. Fading effect - Holding the vehicle and hard repeated braking actions

In case of fading drivers situation awareness should be improved and warning about change in system status should be provided. Progressive support to driver applied force can be performed by active pedal until possible. On human factors point of view, in case of fading drivers situation awareness should be improved and warning about change in system status should be provided.

3.5.7. Stopping in vehicle manoeuvre

Extreme situation of low speed braking. Applied little force on brake pedal vehicle should stop without high amplification. Low dumping, low hysteresis and especially low level of jump-in is required. On human factors point of view, user needs to stop immediately. Braking action needs to be not disturbing or annoying in manoeuvring

3.5.8. Holding the stopped vehicle for restarting on plane road

Brake pedal should ensure vehicle is held. Pedal could represent the situation as in a fixed position with very small travel, e.g. as a ON-OFF toggle command. On human factors point of view, users need to be sure that vehicle is safely stopped but it needs to maintain control of possible movement (i.e. back in movement).

3.5.9. Holding the vehicle and adapt its position on a slope

Brake pedal should ensure vehicle is held and controlled by driver. But ensure also position adjustability. Large travel, low force and large amplification can ensure adjustability. On human factors point of view, user needs is to adjust vehicle positioning in safety, so it needs high level of confidence and self-confidence. High force could be critical to be sustained.

3.5.10. Holding the vehicle stopped for restarting on a slope

Brake pedal should ensure vehicle is held and controlled by driver. Large travel, low force and large amplification can ensure adjustability. With hill holder, it should provide information about self-braking status and incoming changing of status. Pedal idle position should be consistent with self-applied braking. On human factors point of view, user needs to be sure that vehicle is safely stopped but it needs to keep control of possible movement (i.e. back in movement). Users should be aware if function delegated to system change status (self not engagement and back) to ensure trust in automation.

3.5.11. Stop the vehicle and key off - Parking service brake

Pedal should ensure and represent system status also when vehicle is stopped in key off and service brake is actuated. Specific movement to engage service park could be evaluated. Travel can be reduced and pedal resistance amplified. On human factors point of view, user needs to be sure that vehicle is safely stopped but its needs to keep control of possible movement (i.e. back in movement)

3.5.12. On highway, not perform speed reduction but foot touch the brake pedal

Idle travel should be always ensured.

3.5.13. Full loaded vehicle

The pedal amplification should be larger in order to ensure performance. On human factors point of view, users would like to have same braking performance with different levels of vehicle load.

3.6. Scenario – Use Cases Description

So far chapter 3 introduces some high level requirements about the designing of the pedal feelings, from which parameters is afflicted to and how to modify them depending on the related scenario. Starting from situation adapted strategies reported within paragraph 3.5, the relevant scenario situations **Errore. L'origine riferimento non è stata trovata.**could be collected as follow:

- **Adaptation braking:** the user performs a speed reduction or conscious braking action typically while driving at medium-high speed. It is a soft/medium braking, focused on the adaptation to the speed of the vehicle in front of. Example case could be when the driver is adapting the speed in order to make it coherent with the others vehicles and the surrounding.
- **Running;** the user performs a light brake action intentionally or not. In the second case, its foot touches lightly the brake pedal. The braking action is lighter than adaptation braking action. Example case could be when the users slightly touch the brake pedal on highway when others vehicles are in front of the users.
- **Braking action at low speed:** the user is driving at very low speed, typically when the users is performing vehicle maneuvers as parking, stop and on traffic queue.
- **Braking action at low speed with automatic parking system**: the user is driving at very low speed, typically during vehicle maneuvers as parking and stop but in this case with automatic parking system.
- **Emergency braking:** the user performs an high braking action consequently to a risky and unexpected situation on the road. It doesn't care about instant vehicle speed. Example situation could be when some unexpected object are in the vehicle trajectory and the users must stop the vehicle before hit it.
- **Emergency braking with TTC information available:** the user performs an high braking action consequently to a risky and unexpected situation on the road. It doesn't care about instant vehicle speed. Example situation could be when some unexpected object are in the vehicle trajectory and the users must stop the vehicle before hit it: in this case, the UC takes into consideration the time to collision information, which is available as ADAS.
- **Constant speed braking**: the user is driving on a constant slope, continuously using the brake. Example case could be when the users is driving downhill, using several times and endlessly the brake.

- **Repeated hard braking**: the user intentionally performs several emergency braking actions. The behavior is very similar to a sequence of emergency braking actions, but in this case they are expected. Example case could be when the user is driving within a race scenario.
- **Keep the stopped vehicle on plain road before restart:** the user is performing a very common action while driving keeping stopped the vehicle and restart. Example case could be when the vehicle is stopped on a plain road in a traffic queue or stop panel.
- **Keep the vehicle and adapt its position on a slope:** the user is keeping the vehicle stopped on a slope, adapting its position. Example case could be a traffic queue toward a slope.
- **Stop the vehicle, key off and parking brake activation:** a very common action sequence performed by the users: stop the vehicle, switch off the key, park the vehicle activating the parking brake. Actually, the parking brake could be not activated even if the vehicle is parked.

The list describes the use cases in which the users could be involved, covering the major part of normal driving situations. Further explanations about use case criteria are reported in chapter 0.

4. Pedal feeling curves

Chapter 3 details the use cases defined from literature and analysing of normal driving situations. For each of detailed use cases, it is necessary to find out a braking behaviour (i.e. pedal feelings) in order to customize the pedal in function of driving situation. As described in chapter 2, basically, the pedal feeling is a complex phenomenon which takes into consideration several aspects.
Here detailed the most important:

- force feedback on brake pedal;
- deceleration performed and perceived by the user;

For this reasons, these characteristics are good candidates to be variables in order to adapt the pedal feeling behavior in function of the use case. The following paragraphs detail the mathematical parameters which fully describe the pedal behavior in terms of pedal force feedback and deceleration needed. The data were found out following the literature review performed (see chapter 3). Since a lot of use case are defined, a first clustering could be performed in order to reduce the amount, finding out:

- Adaptation braking;
- Low parking braking;
- Emergency braking;
- Constant braking;

All the use cases could be addressed to one of the 4 cases listed above.
The following graphs and tables show the math functions which describe the behaviors of the force feedback and deceleration needed, depending on brake pedal travel.
In all of the graph, it is possible to find out three main sections:

- **idle**: is first part of the graph till 20/25mm of pedal travel: in this part, the pedal feeling are “soft”, both in terms of force feedback and deceleration needed;
- **dosing/normal**: is the central part starting from 20/25mm of pedal travel: in this part the behavior of the pedal feelings starts to be stronger. It is very common to perform brake action in this section;
- **fading**: it is the final part in which the pedal feelings become even more hard. It is uncommon to be in this section, except for the race scenario or following several consecutive emergency braking;

For each section, a broken line describing the math function is shown in the graphs and a row in the tables is provided. The black point on the force feedback line in the graph represents the deceleration equal to 1g. This deceleration is taken as reference. Actually, literature provides different force feedbacks, one for “brake applying” and one for “brake releasing”. Considering the same is on first approximation acceptable because the differences among the curves are minimum.

4.1. Adapt Curve

The following tables and graphs show the math parameters of the adapt pedal feelings.

Force Feedback/ Pedal Travel	m factor	Intercept	Pedal travel X (mm)	Applied pedal Force Fp (N)
	0,000	18,170	0,000	18,170
Idle	0,400	18,170	20,000	26,170
Normal Braking	5,309	-80,000	80,000	344,680
Fading	16,934	-1010,000	102,000	717,217
Deceleration 1 g	5,309	-80,000	65,000	265,053

Deceleration/ Pedal Travel	m factor	Intercept	Pedal travel X (mm)	Deceleration(%) 100% = 1g
	0	0.05	0	5
Idle	0	0.05	8	5
Normal Braking	0.0083	-0.0162	20	14.96
Fading	0.0192	-0.2338	63.3	100

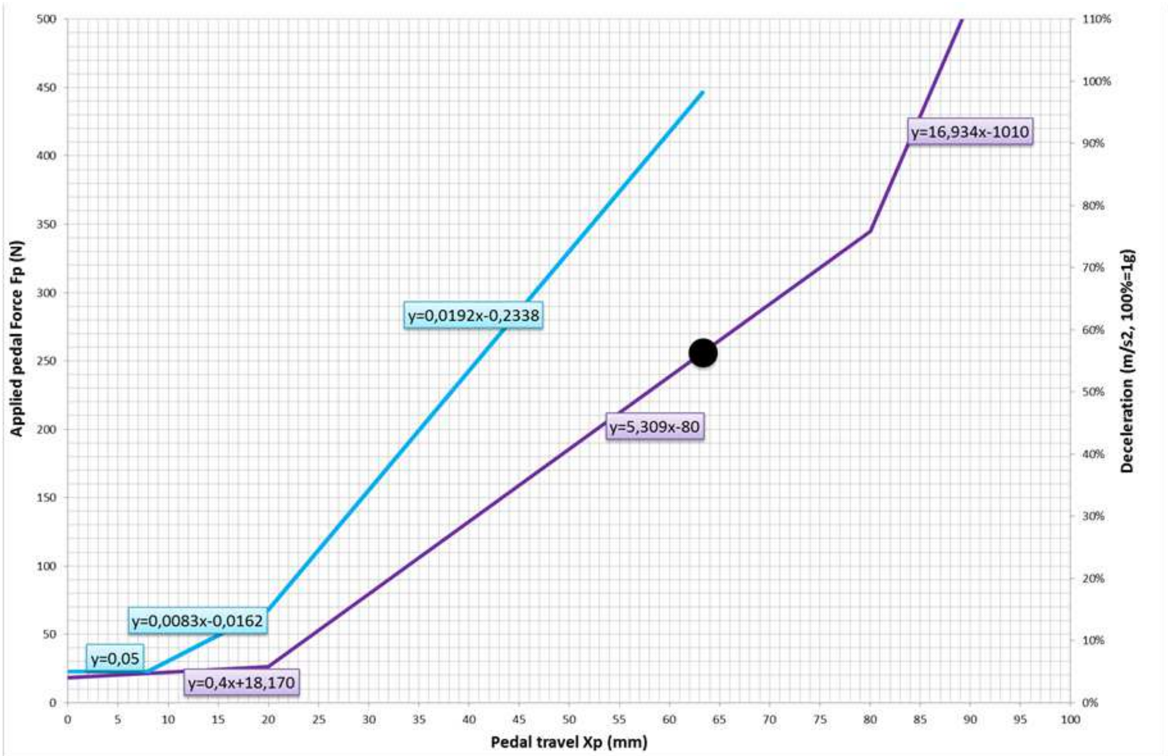


Figure 21: Adapt Curve - Force Vs Pedal Travel And Acceleration Vs Pedal Travel

4.2. Low/Parking Curve

The following tables and graphs show the math parameters of the low/parking pedal feelings.

Force Feedback/ Pedal Travel	m factor	Intercept	Pedal travel X (mm)	Applied pedal Force Fp (N)
	0	18.17	0	18
Idle	1.51	18.17	23	53
Normal Braking	4.3435	-47	78	292
Fading	14	-830	105	640
Deceleration 1 g	4	-27	75	273

Deceleration/ Pedal Travel	m factor	Intercept	Pedal travel X (mm)	Deceleration(%) 100% = 1g
	0	0.03	0	3
Idle	0	0.03	8	3
Normal Braking	0.0071	-0.0269	25	0.1506
Fading	0.0170	-0.2735	75	100

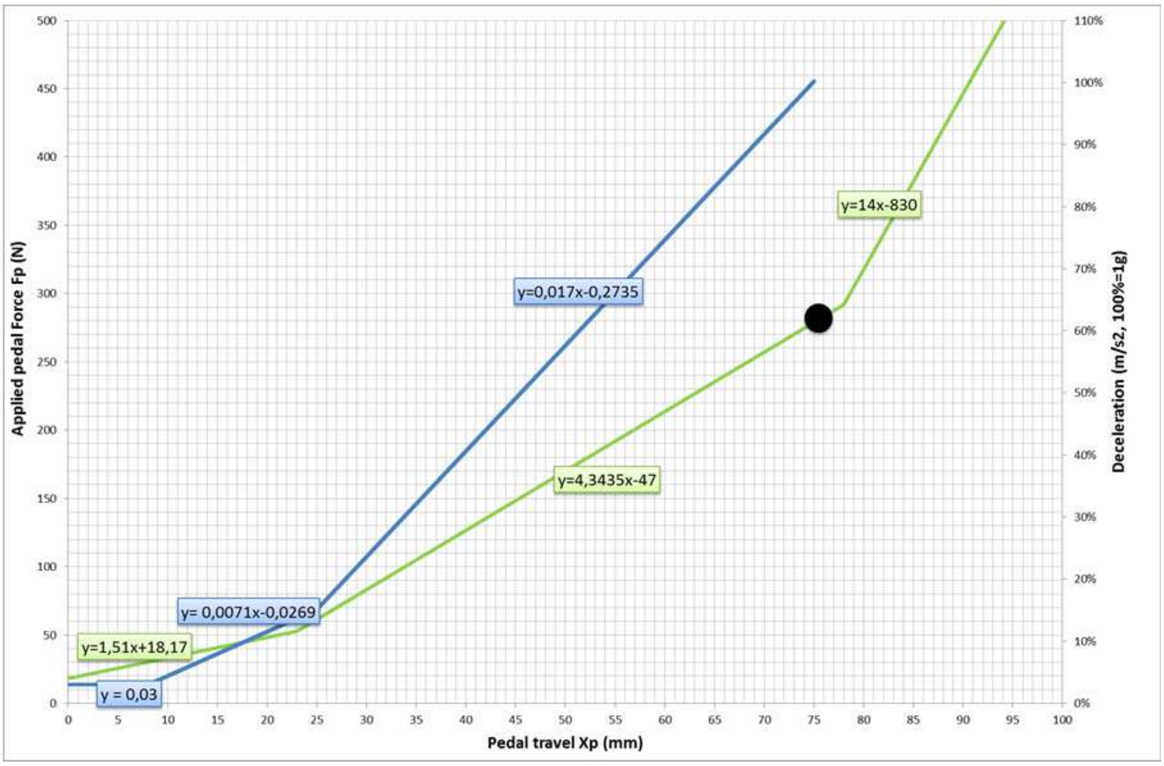


Figure 22: Low/Parking Curve - Force Vs Pedal Travel And Acceleration Vs Pedal Travel

4.3. Emergency Curve

The following tables and graphs show the math parameters of the emergency pedal feelings.

Force Feedback/	**m factor**	**Intercept**	**Pedal travel X (mm)**	**Applied pedal Force Fp (N)**
Pedal Travel	0	18.17	0	18
Idle	1.80	18.17	15	45
Normal Braking	9.70	-118.50	55	415
Fading	21.67	-777	70	740
Deceleration 1 g	9.70	-118.50	30	173

Deceleration/	**m factor**	**Intercept**	**Pedal travel X (mm)**	**Deceleration(%) 100% = 1g**
Pedal Travel	0	0.1	0	10
Idle	0	0.1	7	10
Normal Braking	0.0117	0.0179	15	19.34
Fading	0.0537	-0.6110	30	100

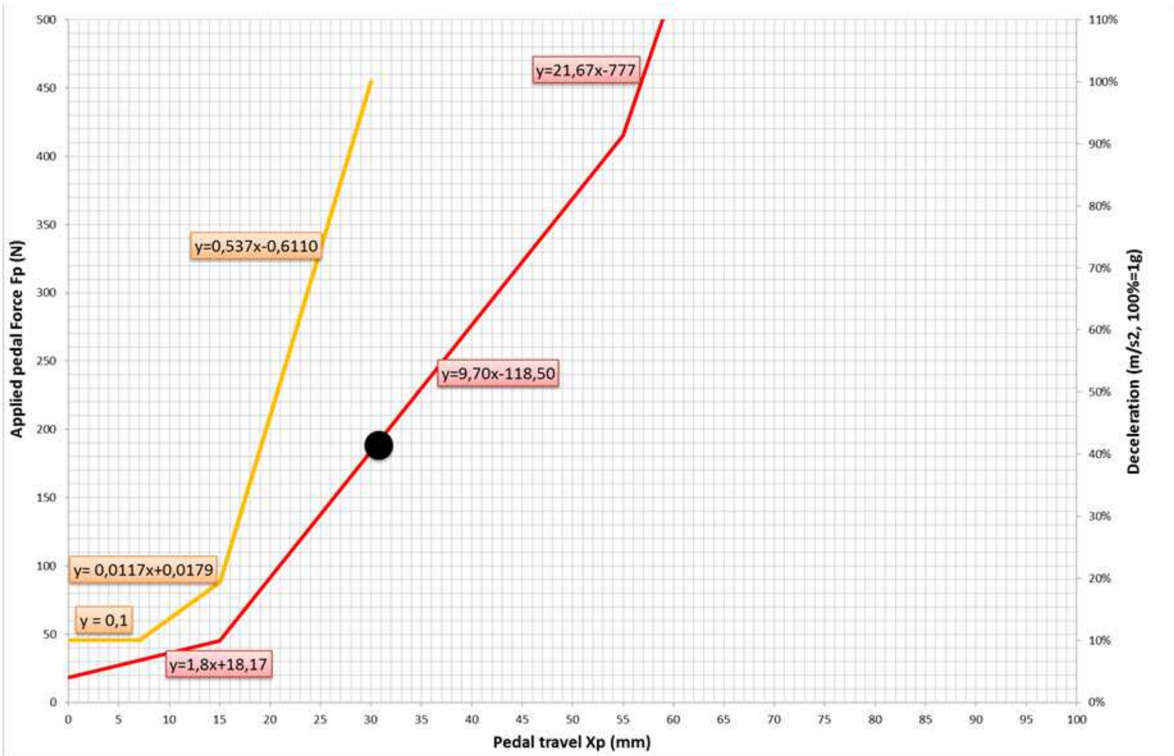


Figure 23: Emergency Curve - Force Vs Pedal Travel And Acceleration Vs Pedal Travel

4.4. Constant Curve

The following tables and graphs show the math parameters of the constant pedal feelings.

Force Feedback/ Pedal Travel	m factor	Intercept	Pedal travel X (mm)	Applied pedal Force Fp (N)
	0	18.17	0	18
Idle	0.80	18.17	20	34
Normal Braking	3.92	-63.00	80	251
Fading	42.50	-3142	90	683
Deceleration 1 g	3.92	-63.00	60	172

Deceleration/ Pedal Travel	m factor	Intercept	Pedal travel X (mm)	Deceleration(%) 100% = 1g
	0	0.08	0	8
Idle	0	0.08	8	8
Normal Braking	0.01	0	20	20
Fading	0.02	-0.2	60	100

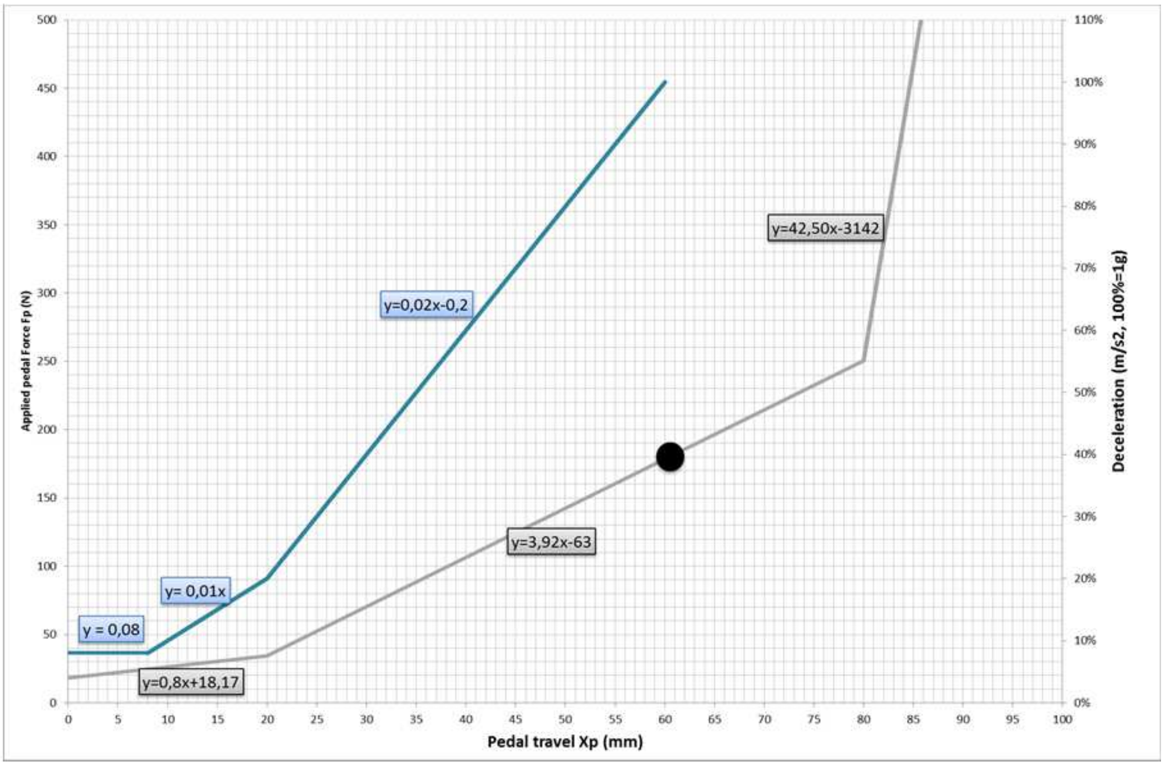


Figure 24: Constant Curve - Force Vs Pedal Travel And Acceleration Vs Pedal Travel

5. Logical Architecture and Implementation

5.1. Logical Architecture Flow

Chapter 5 shows the logical architecture behind the software implementation (paragraph 5.2). This is the rationale flow of the information among user, vehicle and software implementation.
The core of the scenario detection is inside "Observer" module (Figure 25): it is the responsible of braking scenario recognition starting from vehicle dynamic data. In this case, on user point of view, the recognition of the scenario is left to the system. The user could decide to not demand to the system this detection and force it via manual selection. In this case, the "Observer" doesn't perform its job. In case of automatic scenario recognition, "Observer" computes vehicle data input as:

- Vehicle speed and longitudinal acceleration (derived from its speed);
- Brake pedal position and apply speed (derived from its position);
- Gas pedal position and release speed (derived from its position);
- Engine speed;
- 3 axes accelerometers;
- Road slope;
- Key on/off;
- Park system availability;
- TTC availability and (in case) its value;

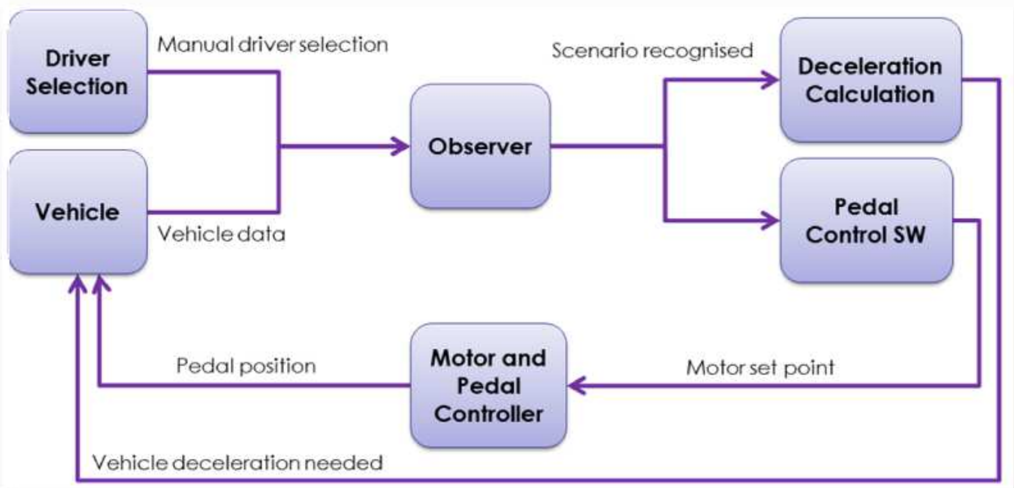


Figure 25: SW Architecture

As output, the "Observer" calculates the relevant scenario as detailed in paragraph 3.6. The output could be:

- Adaptation braking;
- Running;

- Braking action at low speed;
- Braking action at low speed with automatic parking system;
- Emergency braking;
- Emergency braking with TTC information available;
- Constant speed braking;
- Repeated hard braking;
- Keep the stopped vehicle on plain road before restart;
- Keep the vehicle and adapt its position on a slope;
- Stop the vehicle, key off and parking brake activation;

Once the scenario is defined, both modules “Deceleration Calculation” and “Pedal Control SW” take as input the scenario and find out which curve has to be applied.
They calculate respectively the deceleration needed and the pedal force feedback basing on the data shown within chapter 4. The deceleration needed is sent directly to the vehicle ECUs in order to perform the braking action in the 4 wheels corners; the “Pedal Control SW” instead calculates a position of an electric motor which change the displacement of a springs, changing consequently its force feedback.

5.2. Matlab/StateFlow Diagram

The development environment is Matlab® 2010b, jointly with Simulink® and StateFlow® tools.

5.2.1. Macro State

Based on the architecture flow shown on paragraph 5.1, the model firstly has to take care about the connection from/to vehicle in order to collect and send data. The model input is based on CAN and the model output are the command to an electric motor and the deceleration needed.

Figure 26: Model Main Structure

Inside the model, it computes the CAN data in order to detect the input necessary to perform the functions. The main input are detailed in the paragraph 5.1. After that, the model creates some busses in order to send all the information in an easy way, gathering them inside structures.
After that, the model manages the status of the system performing some initial configurations and set up (inside “PedalInit” module) and finally goes in “Run” module. “Debug” is a service module and “Off” is the module that reset the model before restart (see Figure 27). The most interesting module is obviously the “Run” one.

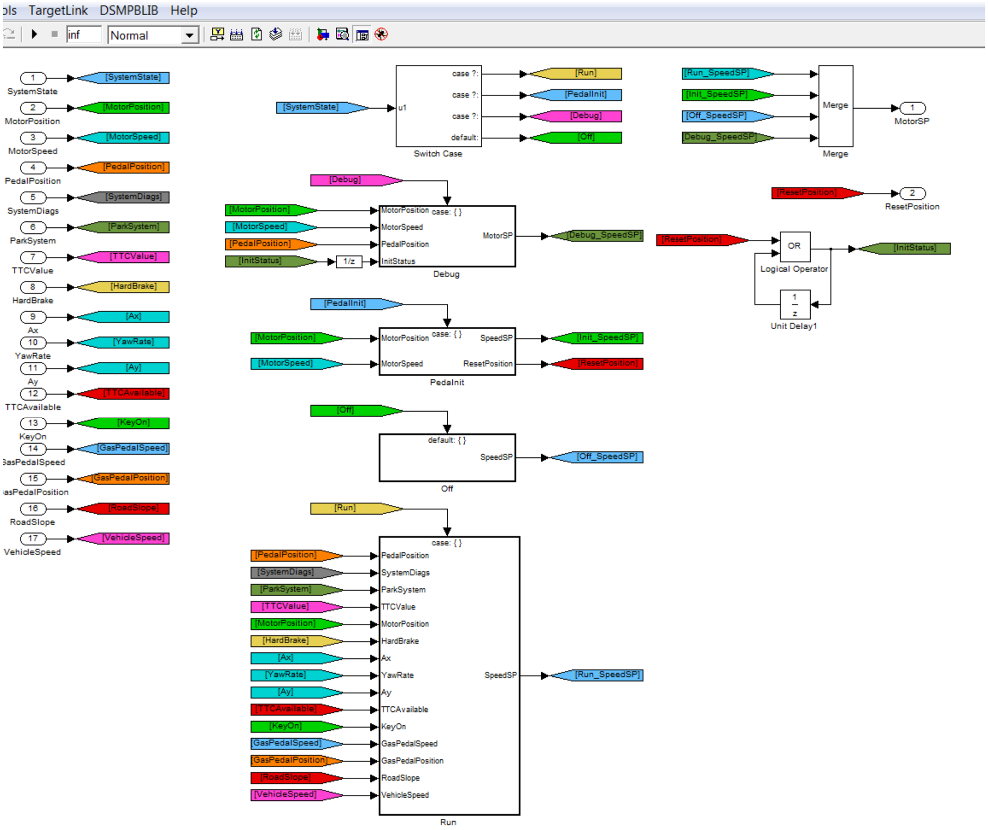


Figure 27: Model: Init State Machine And Control Block

Inside “Run” (see Figure 28), the “Observer” takes the input on the left in order to define the relevant scenario (module output “VehicleState”). “PedalControl” and “AccCalc” blocks takes it as input as reference in order to find out the correct behavior to apply.

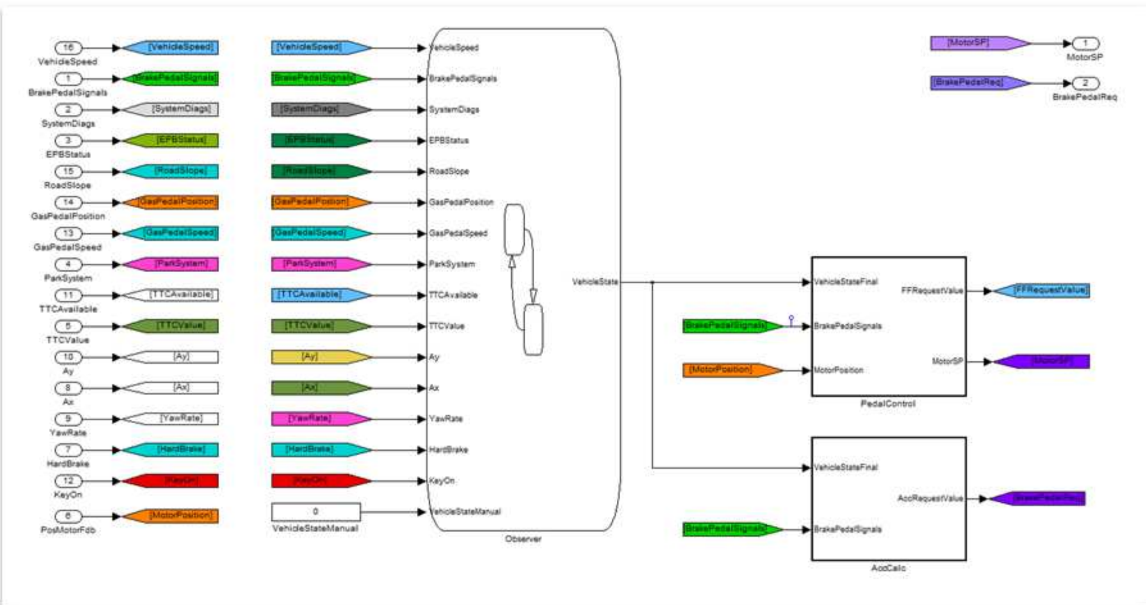


Figure 28: “Observer”, “PedalControl”, “AccCalc”

5.2.2. Observer Module

The “Observer” is a StateFlow® state machine and it is responsible of recognizing the driving scenario. The “Observer” has one state for each driving conditions detailed in the paragraph 3.6, plus one state called “Idle”. The enter conditions of each state are detailed below. The conditions are verified starting from the inputs available (see paragraph 5.1). The output of the “Observer” is a value which indicates the current driving condition (“VehicleState”). The driver can decide to override the scenario identified by “Observer” via the manual command: in case of manual command (see paragraph 5.1), the “Observer” simply provides the scenario defined by the driver. The manual command is intended as a driver selection which prefers a specific pedal feeling instead of the one identified by the “Observer”.

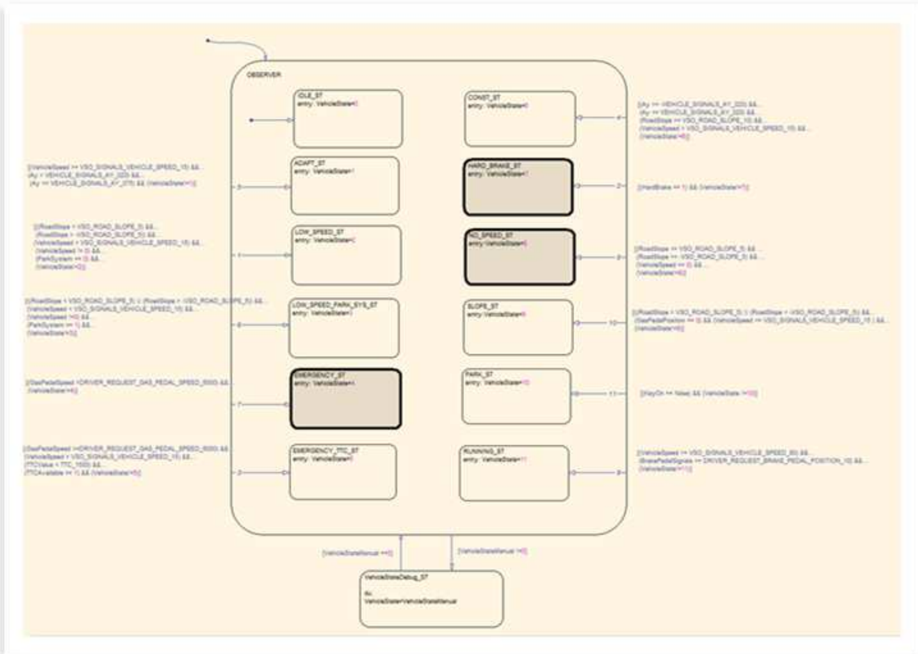


Figure 29: "Observer" Module

5.2.3. States enter conditions within “Observer” module

- **Adaptation braking: ADAPT_ST**
    a. speed >= 15km/h
    b. 0.20g<acceleration< 0.75g
- **Braking action at low speed: LOW_SPEED_ST**
    a. speed < 15km/h and speed != 0 km/h
    b. -5° < road slope < 5°
    c. park system not available
- **Braking action at low speed** (**park system active**) **: LOW_SPEED_PARK_SYS_ST**
    a. speed < 15km/h and speed != 0 km/h
    b. -5° < road slope < 5°

   c. park system available

- **Emergency braking: EMERGENCY_ST**
   a. throttle pedal release speed>= 200mm/s
   b. TTC present not available
- **Emergency braking (TTC available): EMERGENCY_TTC_ST**
   a. throttle pedal release speed>= 200mm/s
   b. TTC < 1,5s
- **Constant speed braking**: **CONST_ST**
   a. 0.2g < acceleration < 0,2g
   b. road slope >= 8° and road slope <=-8°
- **Repeated hard braking** – **HARD_BRAKE_ST**: Similar to several emergency braking actions(e.g. race scenario)
   a. HardBrake input = true;
- **Keep the stopped vehicle on plain road before restart**: **NO_SPEED_ST**
   a. speed = 0km/h
   b. engine rpm > 600 rpm
   c. -5° < road slope < 5°
- **Keep the vehicle and adapt its position on a slope: SLOPE_ST**
   a. road slope >= 8° and road slope <=-8°
   b. throttle pedal position = 0mm
   c. speed <= 15km/h
- **Stop the vehicle, key off and parking brake activation: PARK_ST**
   a. speed = 0km/h
   b. engine rpm == 0 (engine stopped)
- **Running: RUNNING_ST**
   a. speed >= 80km/h
   b. brake pedal position < 40mm
   c. acceleration< 0.20g
- **IDLE_ST:** default state, whenever no other states are available;

5.2.4. State Action/Output

The output of the “Observer” block is an integer which contains the actual scenario.
The relevant value table is the following:

VehicleState	“Observer” State	Short description
0	IDLE_ST	Default state, whenever no other states are available
1	ADAPT_ST	Adaptation braking
2	LOW_SPEED_ST	Braking action at low speed
3	LOW_SPEED_PARK_SYS_ST	Braking action at low speed (park system active)
4	EMERGENCY_ST	Emergency braking
5	EMERGENCY_TTC_ST	Emergency braking (TTC available)
6	CONST_ST	Constant speed braking
7	HARD_BRAKE_ST	Repeated hard braking – race scenario
8	NO_SPEED_ST	Keep stopped vehicle on plain road before restart
9	SLOPE_ST	Keep the vehicle and adapt its position on a slope
10	PARK_ST	Stop the vehicle, key off and parking brake activation
11	RUNNING_ST	Running

Table 5: Driving Conditions Enum

5.2.5. AccCalc Module

The “AccCalc” module is the responsible of the calculation of the deceleration needed. The “AccCalc” module receives:

- the driving condition (“VehicleState” from the “Observer”);
- the brake pedal travel (“BrakePedalSignals” from sensors);

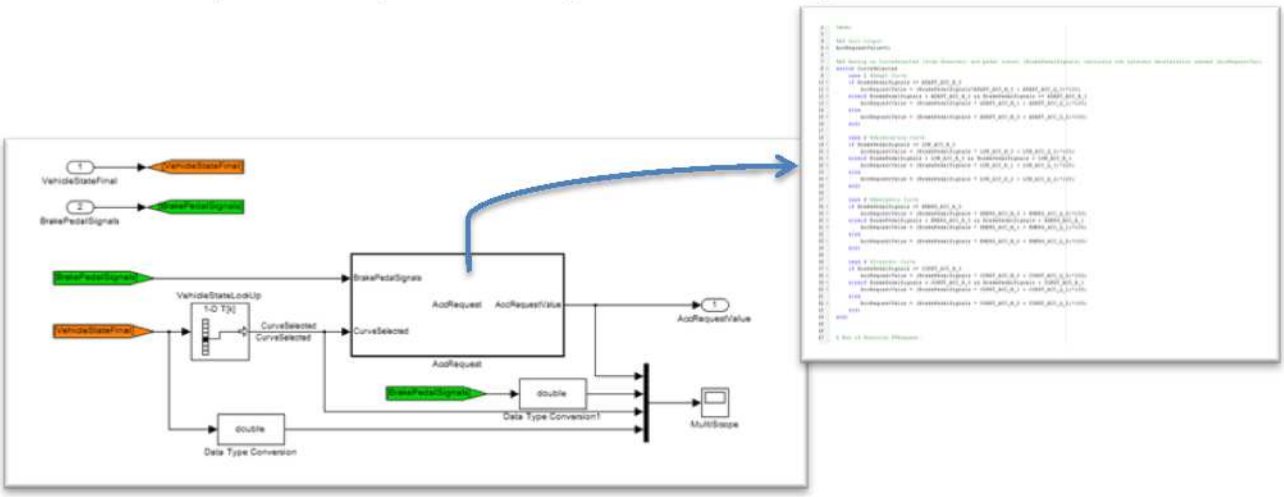


Figure 30: “AccCalc” module

- The “VehicleStateLockUp” module selects the right curve to follow basing on the driving condition detected by the “Observer”. The “VehicleState” is mapped on one of the curve explained in the chapter 4 basing on the Table 6.
- The deceleration needed is calculated by “AccRequest” module via the math formula explained in the chapter 4 .
- The “AccRequestValue” is the output of the module.

Value	State	Curve Selected	Short Description
0	IDLE_ST	1	Adaptation Curve
1	ADAPT_ST	1	Adaptation Curve
2	LOW_SPEED_ST	2	Park/Low Curve
3	LOW_SPEED_PARK_SYS_ST	2	Park/Low Curve
4	EMERGENCY_ST	3	Emergency Curve
5	EMERGENCY_TTC_ST	3	Emergency Curve
6	CONST_ST	4	Constant Curve
7	HARD_BRAKE_ST	3	Emergency Curve
8	NO_SPEED_ST	2	Park/Low Curve
9	SLOPE_ST	2	Park/Low Curve
10	PARK_ST	2	Park/Low Curve
11	RUNNING_ST	1	Adaptation Curve

Table 6: Mapping Vehicle State - Curve Selected

5.2.6. “PedalControl” Module

The “Pedal Control” module is the responsible of the set-up of the mechanical pedal feedback. The “Pedal Control” receives:

- the driving condition (“VehicleState” from the “Observer”);
- the position motor feedback (“PosMotorFdb” from sensors);
- the braking pedal travel (“BrakePedalSignals” from sensors);

and depending on them select the correct behaviour of the brake pedal motor (“VoltageMotorCmd”).

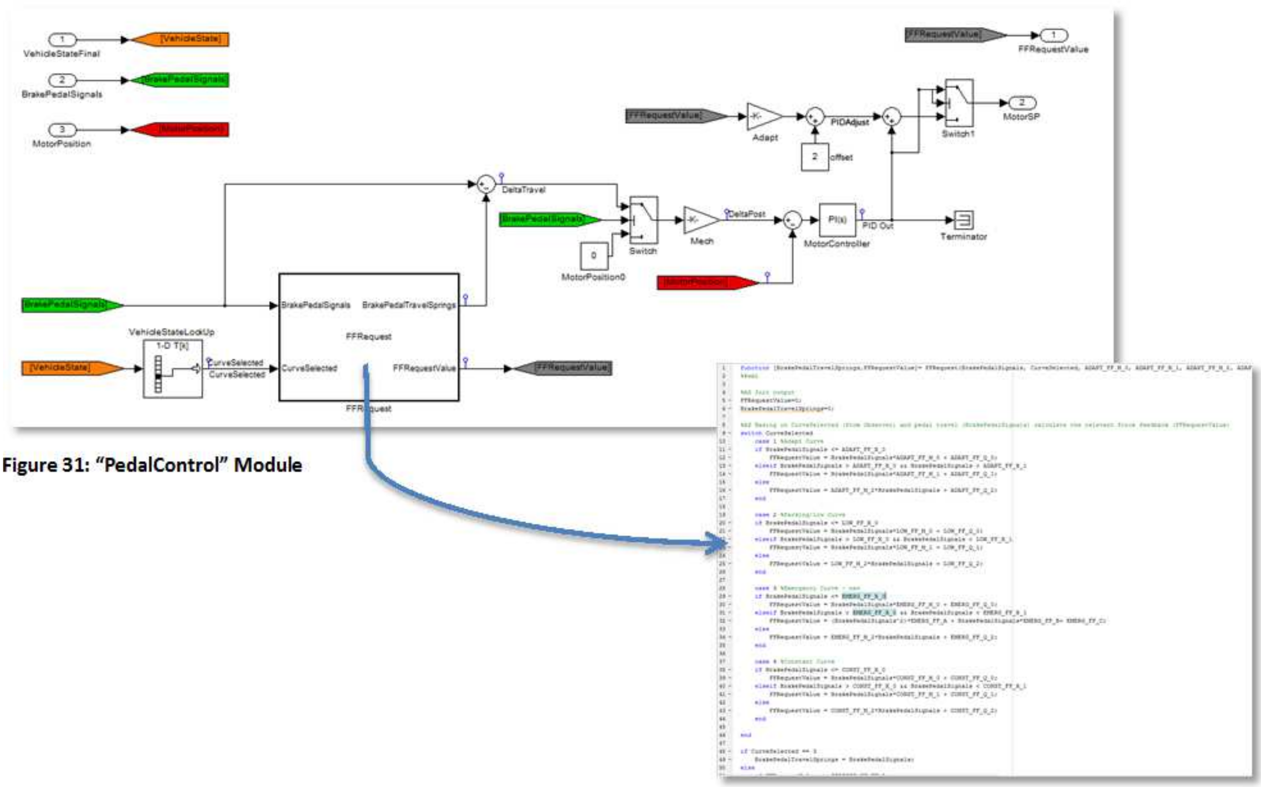


Figure 31: "PedalControl" Module

The "PedalControl" module workflow is the following:

- the "VehicleStateLockUp" block selects the right curve to follow basing on the driving condition detected by the "Observer". The "VehicleState" is mapped on one of the curve explained in the chapter 4 basing on the Table 6.
- the "FFRequest" block is the responsible of the calculation of the force feedback needed ("FFRequestValue") basing on the curve selected and the braking pedal travel. Once the force feedback is calculated, the "FFRequest" block detects the relevant pedal travel ("BrakePedalTravelSprings") considering only the springs without the motor contribution;
- the difference among "BrakePedalTravel" and "BrakePedalTravelSprings" is the travel amount the motor has to cover (before the switch in the Figure 31);
- if the "BrakePedalTravel" is minor than 3mm, the "BrakePedalTravel" is considered as 0;
- the motor control is based on a PID controller, which has the position error as input;
- after that, the block perform an "adaptation" of the set point considering how much is the force on the pedal travel in order to be, in case, stronger;
- as output, the "PedalControl" module returns the action to do on the motor ("MotoSP").

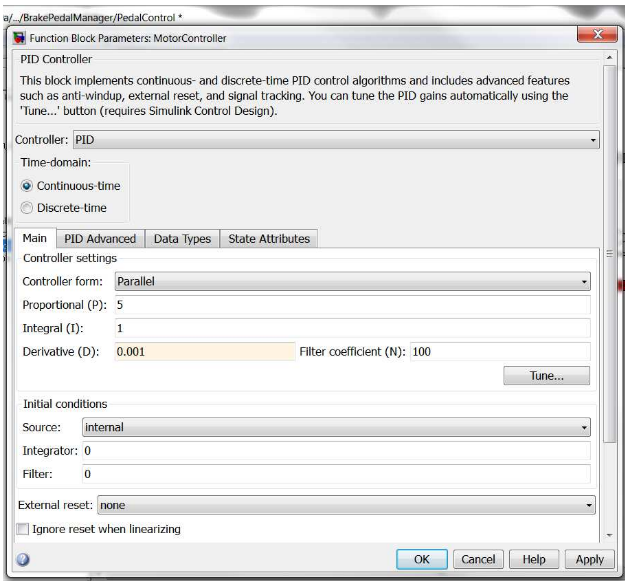


FIGURE 32: PID SETTING

5.3. Model Simulation & Deploy

5.3.1. Model Simulation

Since major information are provided via CAN input, model simulation has been firstly performed via static input in order to progressively control the flow of the model information and the main output. The solver is ode3 (Bogacki-Shampine) and step size is fixed to 0.005s.
The main preliminary debug has been focused on the "Observer" module in order to check if the transitions and the "VehicleState" calculation works correctly. Once this signal has been checked, the debug carried on checking both "PedalControl" and "AccCalc" modules which take "VehicleState" as input.

5.3.2. DSPACE MicroAutoBox HW

DSPACE MicroAutoBox is a real-time system for performing fast function prototyping in fullpass and bypass scenarios. It operates without user intervention, just like an ECU. MicroAutoBox can be used for many different rapid control prototyping (RCP) applications such as:

- Drives control
- Chassis control
- Powertrain
- Body control
- X-by-wire applications

5.3.3. Model Deploy on DSPACE

Once relevant DSPACE packets are correctly installed within Matlab®, is it possible to use DSPACE block directly form Simulink® library (see Figure 34).

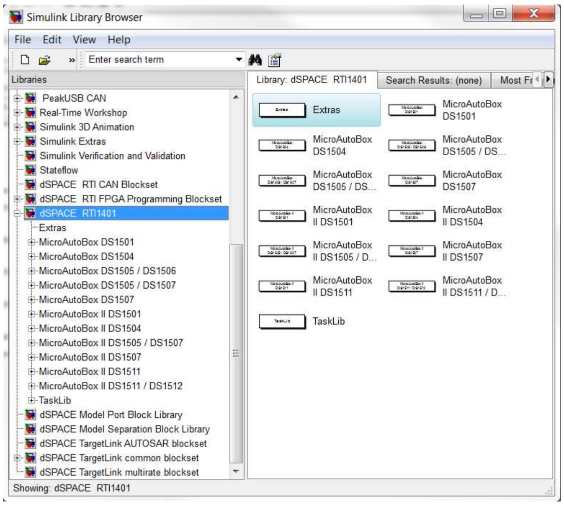


Figure 34: Simulink® Library with DSPACE components

The library component allows you to interact with key features of DSPACE MicroAutoBox, like A/D converter and CAN bus interface. In this way, it is possible to read/write data on the CAN and on the A/D directly from the Matlab® model developed so far.
Regarding the CAN, once set up on the main characteristic of the bus and of the signals (e.g. scaling factor, type of data, offset, name, etc), the relevant blocks give back as output the physical signal to use in the model.
Regarding A/D, each DSPACE block within the library has to be set up in order to match the signal characteristic and physical HW port on which it is connected.
Once blocks are correctly set up, the model could be deployed for the DSPACE MicroAutoBox. The compiling output are several files, but the most important are:

- modelName.ppc: it's the binary file that contains the application;
- modelName.sdf: it's the variable definition file in order to actively interact with the application in the DSPACE Control Desk tool.

DSPACE Control Desk is the experiment software for seamless ECU development. It performs all the necessary tasks and gives you a single working environment. Control Desk provides access to variables stored and running on the model, reading and writing them. The files .ppc and .sdf have to be loaded inside the current Control Desk project/experiment in order to flash them on the DSPACE MicroAutoBox memory. Once loading success, the model is running on the target.

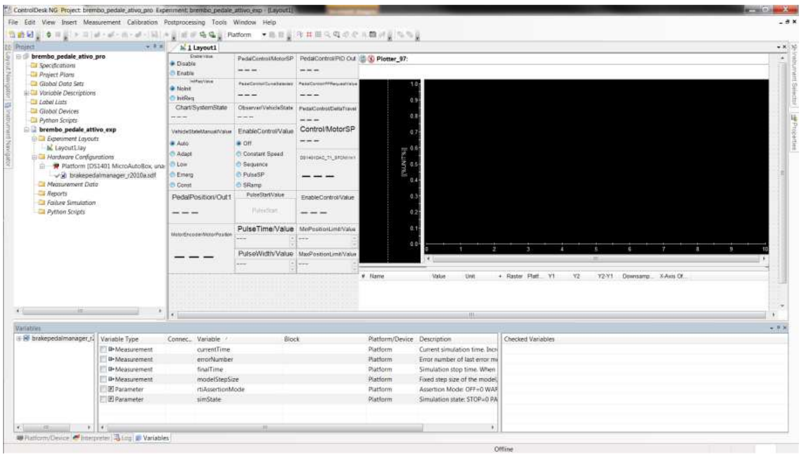


Figure 35: DSPACE Control Panel

Control Desk is a powerful tool and through it is possible to carry on the debug began in the paragraph 5.3.1, analysing dynamic data and modifying variables (defined in .sdf file) in real-time until the whole model works as expected.

6. Model Validation Through Experimental Vehicle Data

During paragraph 5.3.1 some debug tasks have been performed in a controlled environment in order to check the model running on the target. In principle, the "Observer" block is the main module which read the input data. The data provided to the model were static and generated by other tools and may be very different from the real data. For this reason some data collection trials have been performed on the real road with a real vehicle. The objective of the tests is to collect data to use during bench test in order to deeply debug and validate the model (i.e. "Observer"). In fact, storing data from real trials has the advantage to perform some more reliable tests on the model modules.

6.1. Vehicle Integration

The model validation consist of a cluster of trials with a real vehicle, a Lexus 220d, equipped with a custom ECU in order to read data directly from the CAN network (via OBD connector). Relevant data is sent via Bluetooth to a smartphone placed into the vehicle (see Figure 36).

Figure 36: HW Integration Via OBD

A custom application runs over the smartphone and it has 3 main objectives:
- store the data received via Bluetooth;
- integrate the data received via Bluetooth with native accelerometer/gyrometer data;
- create a log with the data (CAN Vector format .asc) in order to reproduce during bench test;

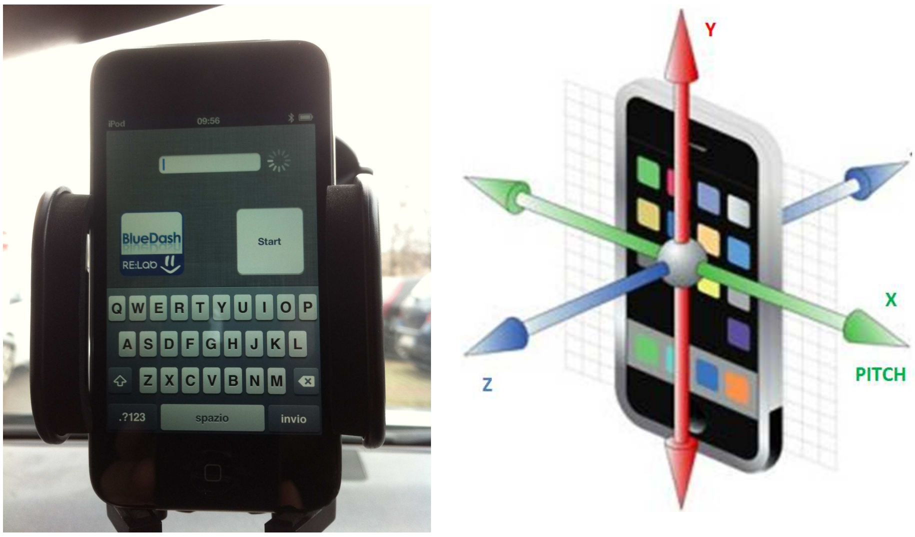


Figure 37: Data Collection Via Smartphone & Smartphone Axis

The data collected covers the necessary data for the "Observer" enter conditions. Some more data have been stored but they have not been used.
The trails could be gathered in two main steps:

- trials addressed on initial revision of the conditions detailed in the paragraph 5.2.3;
- trials addressed on the data collection for model debug and validation;

The first cluster of trials have been focused on the collection of the dynamic data theoretically defined during model development. The threshold parameters detailed in the paragraph 5.2.3 are already the correct one. Some refinements have been necessary on some parameters. Basically, they are:

- brake pedal release speed:
- gas pedal release speed;
- road slope;
- longitudinal acceleration;

Once checked on the smartphone log the data collected, a first revision of the enter conditions have been performed in order to define better the entry state thresholds of the signal listed.
The second cluster of trials consists of several separate runs with specific objectives and conditions. This trial cluster has been focused on the data collection in order to debug and validate the Matlab® model. Trials have been performed following the use cases defined in the paragraph 3.6 (except the ones with ADAS) in order to reproduce the same conditions detailed in the paragraph 5.2.3 and revised above. In particular, for each use case, 3 separate trials have been performed in order to have much more data to use.
In addition, 3 trials have been performed with no restrictions and logging the various scenario conditions encountered.
Once collected, the data have been analyzed on bench in order to check it and reproduce on a CAN network as a input for the model.

6.2. Trials Data

The paragraph 6.2 summarize the results of the trials. Despite 3 trials per each use case were performed, just one trial log is shown per each use case.

6.2.1. Adaptation braking

The Figure 38 shows 3 brake actions (red line) referenced to time (X axis, more than 40seconds). The brake actions are typical for adaptation braking as defined in chapter 4. Other data are direct connected/consequences of brake actions. The vehicle speed is intentionally maintained within the correct speed domain (Y axis on the right) in order to reproduce the adaptation brake case.

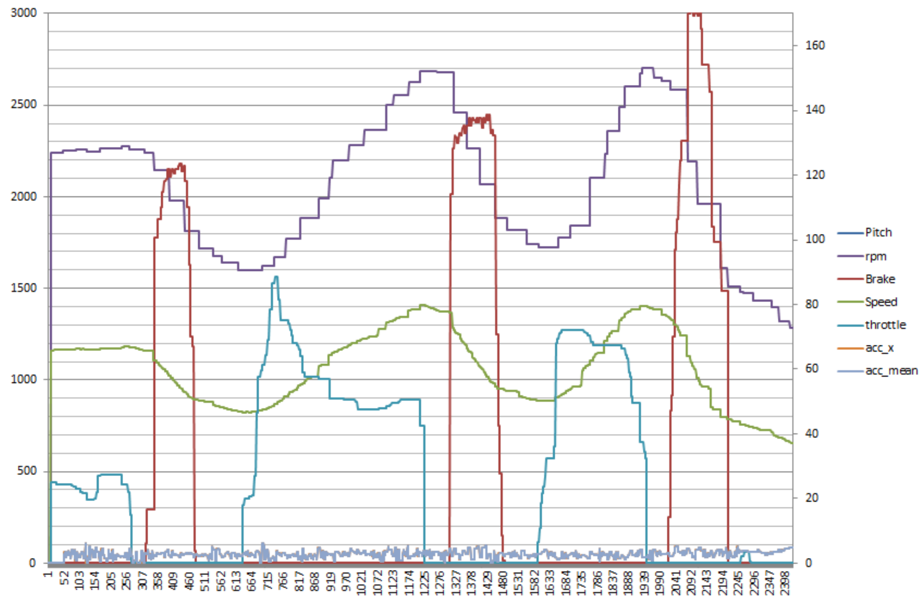


Figure 38: Adaptation Braking

6.2.2. Running

The Figure 39 shows 5 brake actions (red line) referenced to time (X axis, more than 90seconds). The second brake action is typical for adaptation braking: it is within this graph in order to perform a visual comparison. Except the second one, the others brake actions are the running brakes as defined in chapter 3. It is clear from the graph that the running brake is lighter than the adaptation one. Other data are direct connected/consequences of the brake actions.

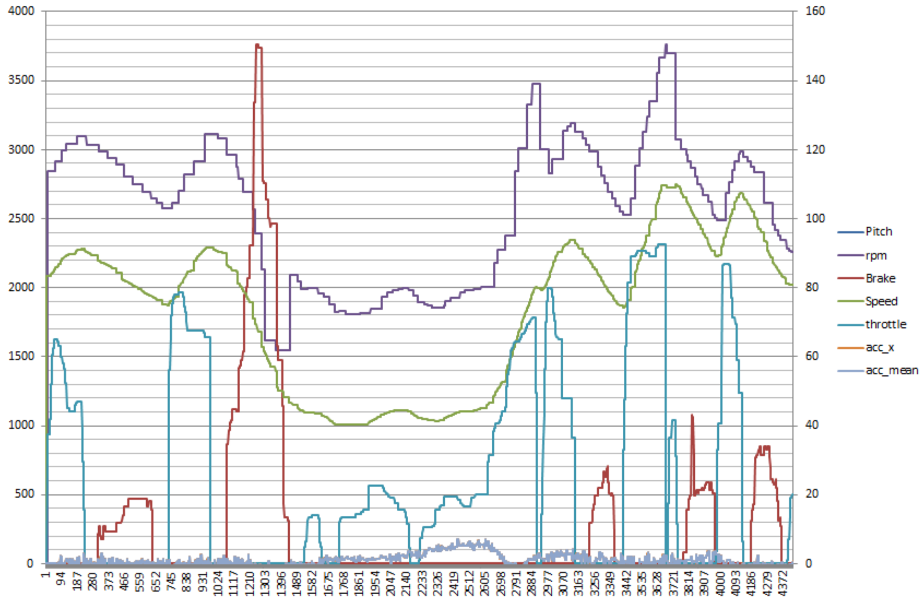


Figure 39: Running

6.2.3. Braking action at low speed - Park/Stop

The Figure 40 shows 4 brake actions (red line) referenced to time (X axis, more than 40seconds). The brake action is typical for braking at low speed as defined in chapter 4. Other data are direct connected/consequences of the brake actions. In particular, the vehicle speed is very low (below 15 km/h, Y axis on the right) in order to reproduce the low speed case.

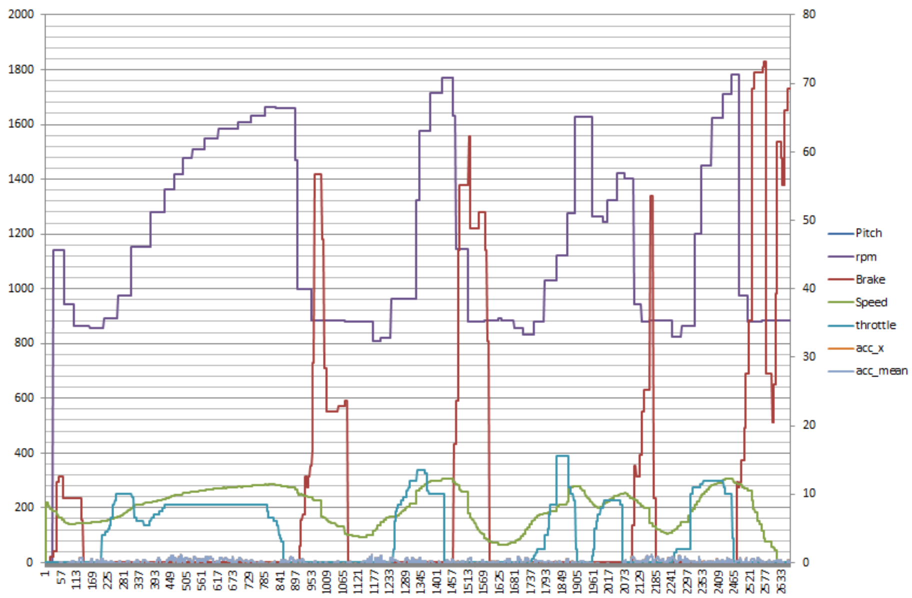


Figure 40: Braking Action At Low Speed

6.2.4. Emergency braking

The Figure 41 shows 1 brake action (red line) referenced to time (X axis, more than 50seconds). The brake action is typical for braking in emergency situation as defined in chapter 4. Other data are direct connected/consequences of the brake actions. In particular, it is very interesting the behavior of the position of the throttle pedal which is released very fast (7 times for test): how much fast, is an important information for emergency state enter conditions of the “Observer”.

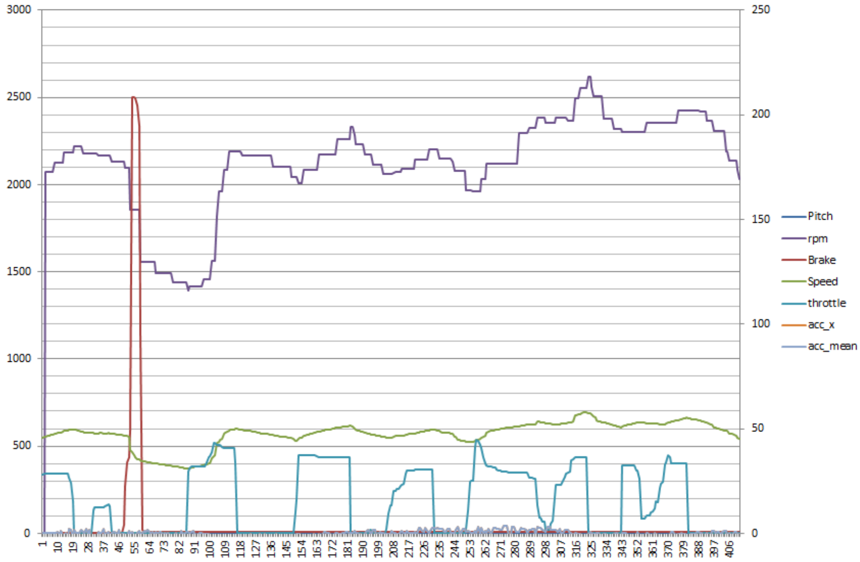


Figure 41: Emergency Braking

6.2.5. Constant speed braking

The Figure 42 shows some brake actions (red line) referenced to time (X axis, 120seconds). The brake action is typical for braking on slope road (e.g. downhill) with speed different from zero as defined in chapter 4. The road slope is identified by pitch signal (blue line) and in this case it is 20° at maximum (Y axis, right scale).

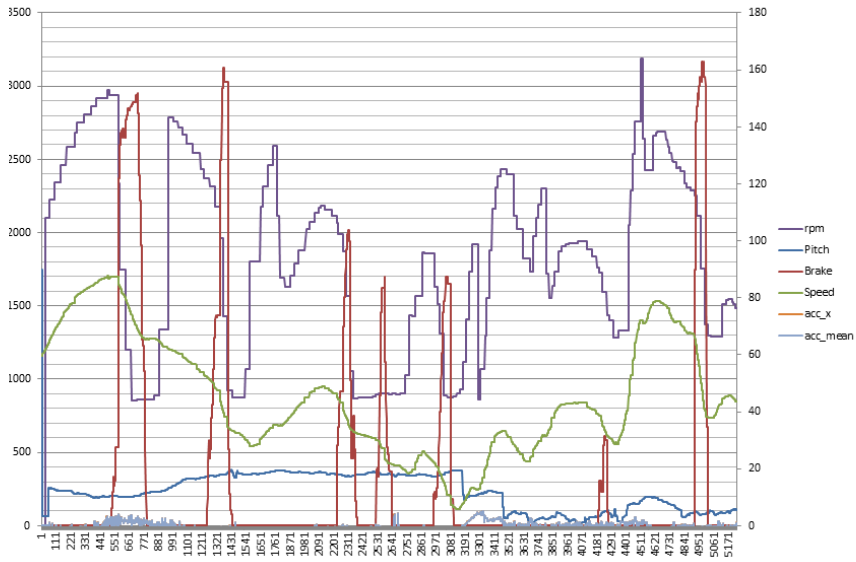


Figure 42: Constant Speed Braking Data Collected

6.2.6. Repeated hard braking

The repeated hard braking use case is very similar to the emergency one: in fact, it is composed by a series of emergency braking and for this reason it could be gathered to it.

6.2.7. Keep the stopped vehicle on plain road before restart

The Figure 43 shows the brake action (red line) referenced to time (X axis, 20seconds). The brake action is typical for braking on plain road with no speed as defined in paragraph 3.6. Engine speed is the minimum level (e.g. 800 rpm).

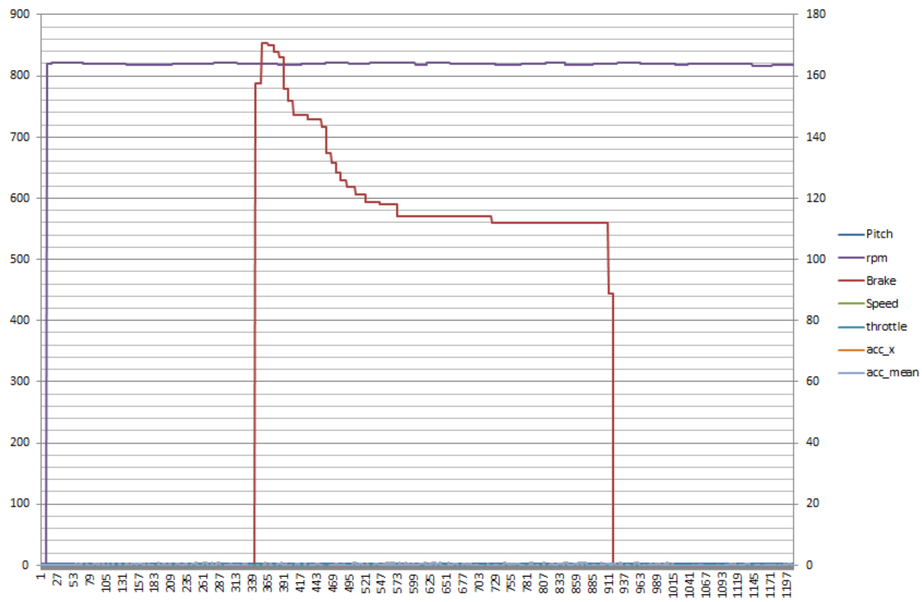


Figure 43: Plain Road And Restart

6.2.8. Keep the vehicle and adapt its position on a slope

The Figure 44 shows a couple of brake actions (red line) referenced to time (X axis, 60seconds). The brake action is typical for braking on a road slope (or few moments before), adapting the position on the road slope, as defined in paragraph 3.6. The road slope is identified by pitch graph (blue line) and it is 9° at maximum (Y axis, right scale). Other data are direct connected/consequences of the brake actions.

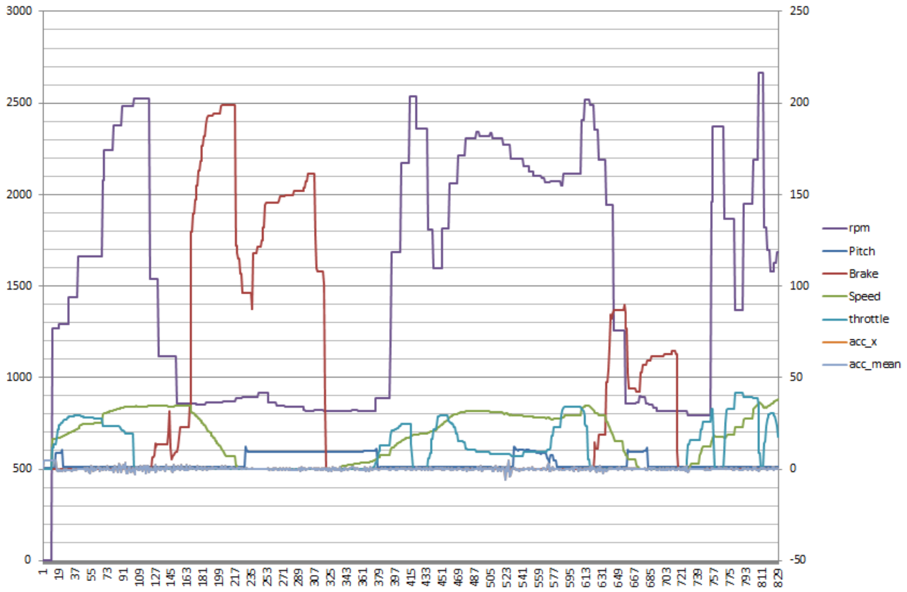


Figure 44: Keep The Vehicle And Adapt Its Position On A Slope

6.2.9. Stop the vehicle, key off and parking brake activation

This case is very similar to the “Keep the stopped vehicle on plain road before restart”: in fact, the variables are the same plus both key off and parking brake signal in the end. The order doesn’t care. Actually, the vehicle could be parked without parking brake.

6.2.10. Mixed Scenario

The Figure 45 shows the data collected in a mixed scenario referenced to time (X axis, 140seconds). Since they are the ones within normal scenario, they will be the most complicated cases. It is expected that the “Observer” makes several changes during the logs. During the trials, notes have been taken in order to check the use case detected with the one really encountered.

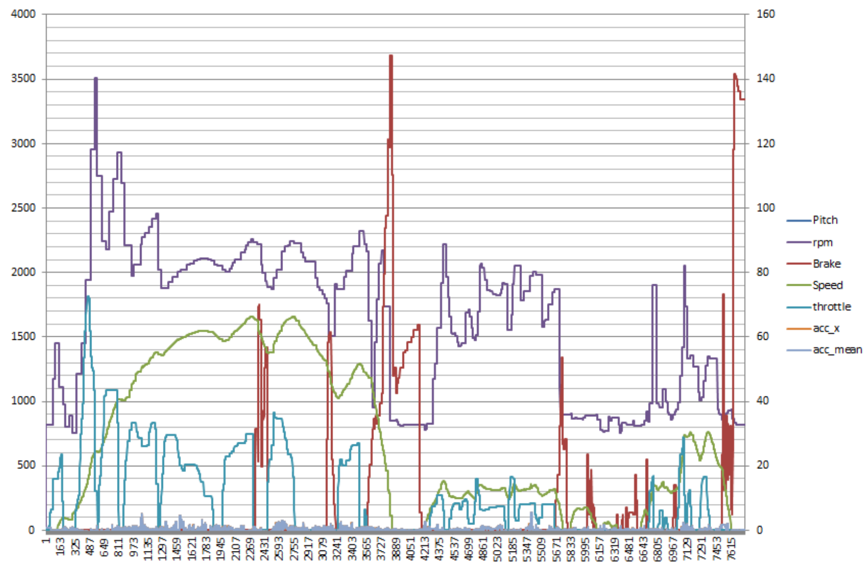


Figure 45: Mixed Scenario

6.3. Bench Preparation

Once the logs are briefly checked (see paragraph 6.2), the data are ready to be processed by the model. In order to provide them through DSPACE tool chain, some phases have to be performed. The log are stored in a .asc files, with the vector format: in this way, it is possible to replay the log through a Vector CANOe software and Vector CAN device (CANCase XL).

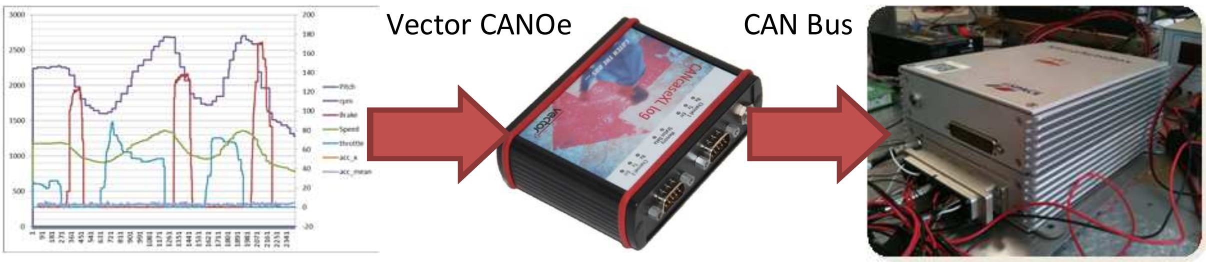


Figure 46: Log Replay Chain

As stated in paragraph 5.2.1, the original model has CAN input module which has to be set up with the CAN messages and signals through proprietary DSPACE blocks (placed in the Simulink® Library as mentioned in 5.3.3). Once the cabling regarding power supply and CAN bus are done, the DSPACE is able to be connected to the CAN in order to read the data sent from Vector CANOe. A first check could be performed directly in DSPACE Control Desk which makes you able to have a look to the variables stored in the model and red from the bus.
Playing different log files, the “Observer” should have different output values.

6.4. Validation Results on “Observer” module

The focus of the validation is the analyses of the “Observer” module behavior running on DSPACE MicroAutoBox. The input data are provided via CAN interface and they are relevant to the different logs (i.e. use case) explained in the previous paragraphs.

Case	Log Success	Note
Adaptation braking	3/3	Looking at the data, some adjustments have been needed in the acceleration thresholds in order securely detects the use case. In particular, the lower threshold have been moved from 0.20g to 0.15g and the upper one from 0.75g (too high) to 0.50g.
Running	2/3	In one case the “Observer” detects adaptation use case. This is due the modification done before: For this reason the upper threshold have been moved from 0.20g to 0.15g in order to not overlap the

		Adaptation state when the vehicle speed is in the same domain.
Braking action at low speed	3/3	The logs raised the fact that this use case is valid till the vehicle is moving: when the vehicle speed is 0, the “Observer” correctly switches on the use case named “Keep the stopped vehicle on plain road before restart”.
Emergency braking	3/3	A key role has been played by the first cluster of trial which give back a reasonable value for the throttle pedal release speed.
Constant braking	2/3	The one didn’t recognize was uphill. In fact, the enter transition regarding “Constant” use case doesn’t take care about negative degrees. One further comment on the acceleration thresholds in the enter transition: they could be not necessary but experimental data shows that typical accelerations are within this range.
Keep the stopped vehicle on plain road before restart	3/3	The logs raised the fact that this use case is valid till the vehicle is stopped: when the vehicle speed is different from 0, the “Observer” correctly switches on the use case named “Braking at low speed”.
Keep the vehicle and adapt its position on a slope	3/3	There were a clear conditions regarding vehicle absolute pitch and speed. One comment regarding the threshold: sometimes some roads that are intended as “plain” have inclination upper than 5 degree, which is the threshold of the state. In case, this value could be raised to 7-8° in order to have a wider difference among these use cases. On other hand, “Keep the stopped vehicle on plain road before restart” should include values till 7-8°
Stop the vehicle, key off and parking brake activation	3/3	Clear conditions regarding the key off. Actually, the parking brake activation signal is not present in enter transition because of the vehicle could be parked without it.
Mix Use Case		Some difficult interpretations has been encountered during the transition among adaptation and running use cases, especially when the acceleration pass through the threshold. Other states have been identified well (emergency brake event doesn’t occurred and the driver forced it).

Table 7: Validation results on "Observer"

6.4.1. Repetition of all the tests

The tests has been repeated with all the 24 logs with the modifications done in the previous paragraph and the “Observer” detects the correct use case in 100% of the case.

6.5. Validation Results “AccCalc” and “PedalControl” module

Once the “Observer” is validated and the correct use case is detected, the model proceed with the calculation of the deceleration needed and with the motor set point (see paragraph 5.1).
Regarding the deceleration needed, a function in a subsystem takes care about the calculation described in the chapter 0: a validation has been performed forcing the brake pedal travel (on the X axis in the graph within chapter 0) to an incremental static value and checking the relevant output value.
Regarding the motor set point, the “PedalControl” validation has been separated in two main parts:

- calculation of the “BrakeTravelSprings”;
- calculation of motor set point;

For the “BrakeTravelSprings”, the followed procedure is the same of the deceleration needed: tests with incremental static value and checking the relevant output value.
A further adjustment has been necessary in order to make it working as desired: in fact, the force applied by foot (or actuator) to the pedal makes the movement of the motor lighter or harder, depending on the versus of the pedal movement.
For this reason, it has been necessary to introduce a proportional contribution in function of the “FFRequest” calculated (see top right of the Figure 31).
For the motor set point, it has been necessary to prepare a bench test equipped with a real motor. A first step is to check the PID parameters. Chapter 7 shows how the motor behaves in function of different input. Once set up the parameters, the DSPACE output has been checked in order to control the voltage command to provide to the motor.

7. Tests on closed-loop motor controller

7.1. EC Motor

The selected motor is a Maxon EC MOTOR 118893, equipped with Maxon HEDL 5540 encoder. The driver ECU used is a standard one directly provided by Maxon.

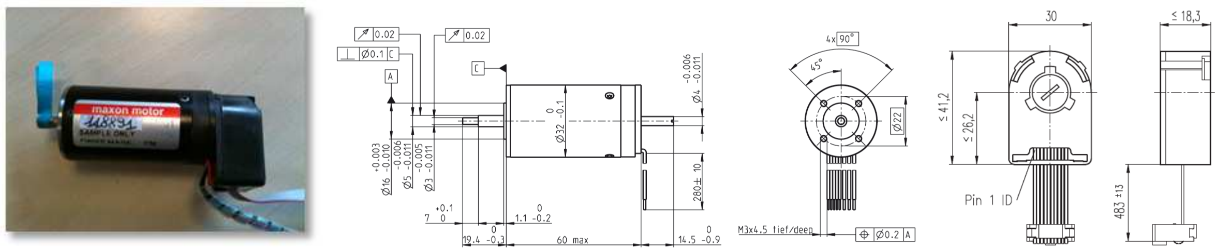


FIGURE 47: EC MOTOR AND ENCODER

7.2. Motor Control Test Environment

The motor control is a PID controller on position feedback of the motor. The connection among motor and Matlab® environment is performed by the module shown in the Figure 48 which contains the DSPACE components needed to acquire the motor position feedback and to set the motor voltage set point. The PID constants for the tests shown below are:

- Kp=0.9;
- Ki=1;
- Kd=0.01;

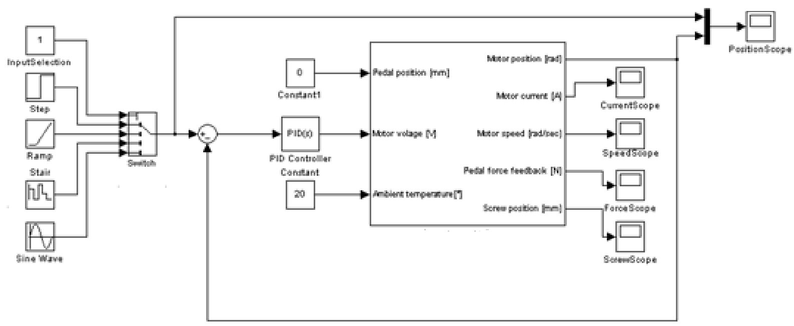


Figure 48: Motor Control By PID Controller

The tests are based on the following input:

- Step;
- Ramp;
- Stair;
- Sine

7.3. STEP INPUT

- Step time: 3
- Initial value: 0
- Final value: 5

Actual motor position (magenta) and step input (yellow) are shown in the Figure 49.

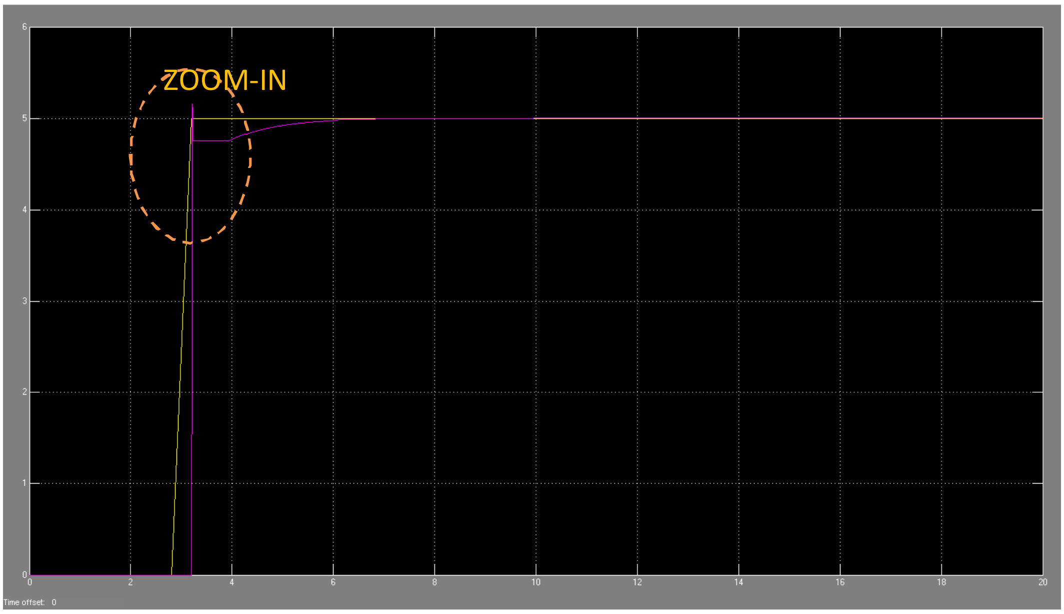


Figure 49: Motor Position (Magenta) Vs Step Input (Yellow)

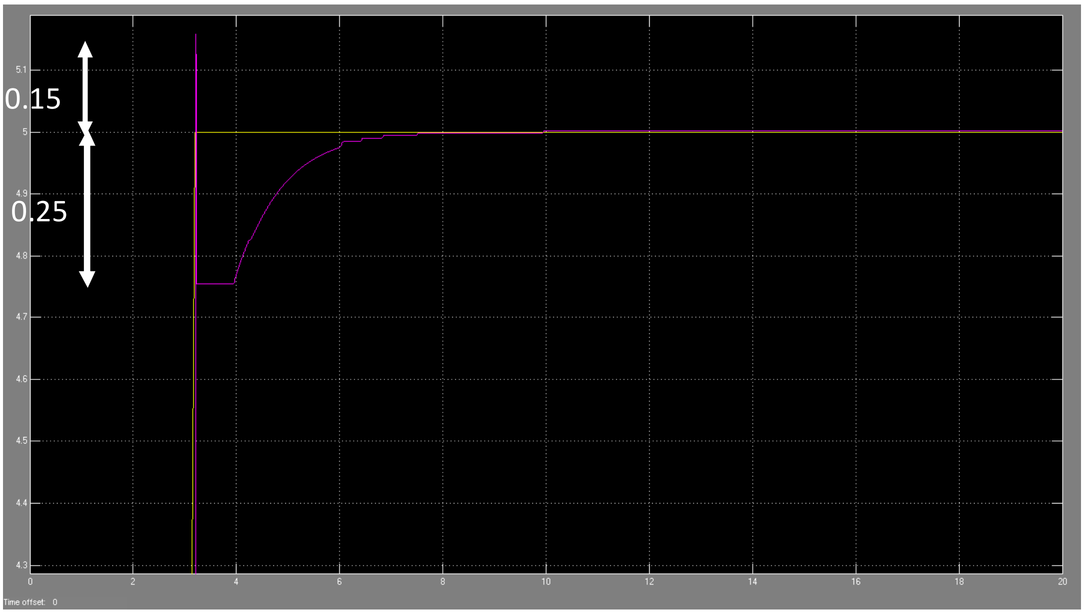


Figure 50: Motor Position (Magenta) Vs Step Input (Yellow) - Zoom-In

7.4. RAMP INPUT

- Slope = 1;
- Start time = 0;
- Initial output = 0;

Actual motor position (magenta) and ramp input (yellow) are shown in the Figure 51.

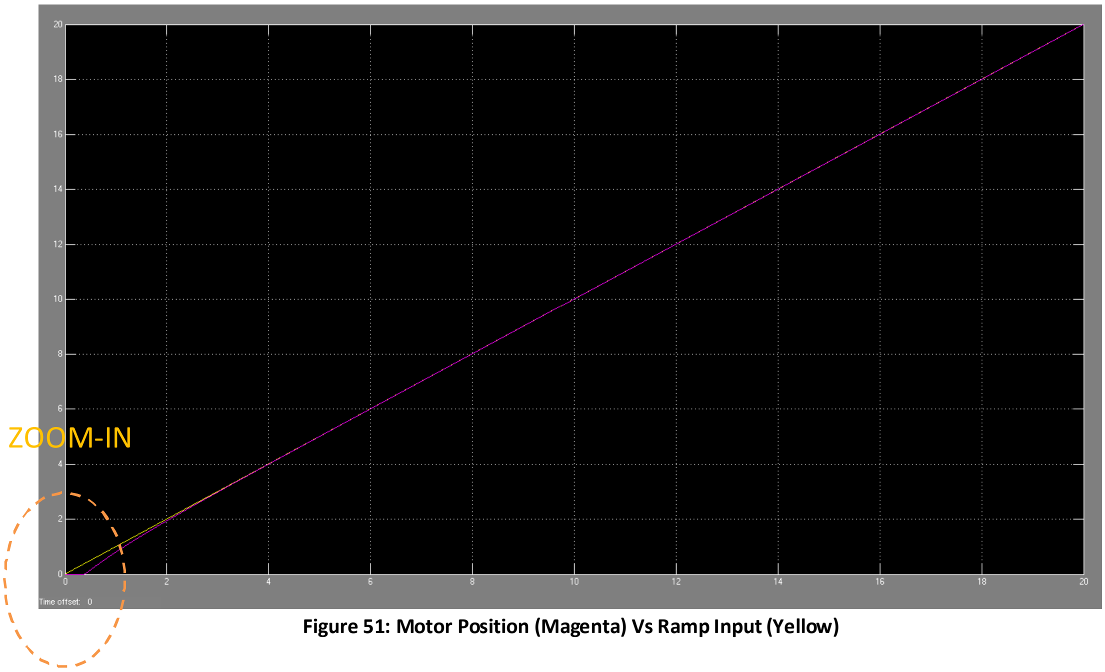


Figure 51: Motor Position (Magenta) Vs Ramp Input (Yellow)

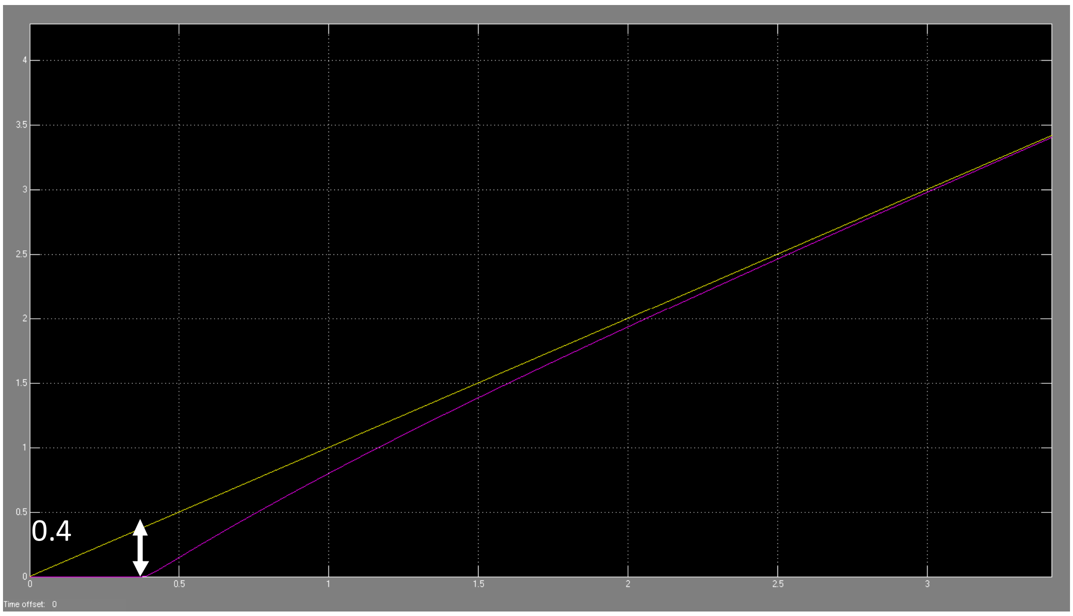


Figure 52: Motor Position (Magenta) Vs Ramp Input (Yellow) - Zoom-In

7.5. STAIR INPUT

- Vector of output values: [3 1 4 2 1];
- Sample time = 2;

Actual motor position (magenta) and step input (yellow) are shown in the Figure 53.

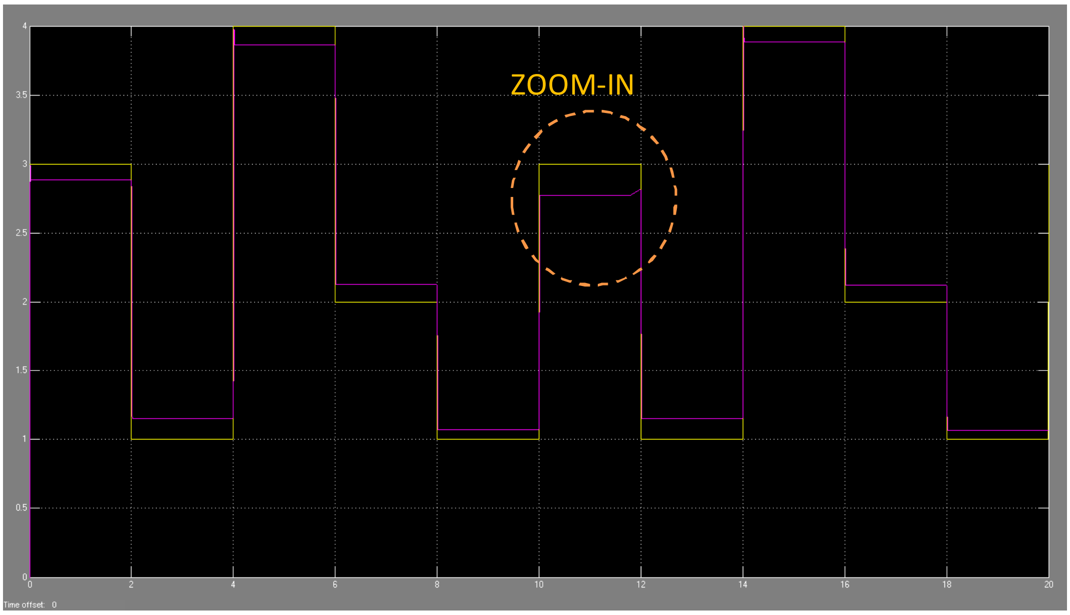


Figure 53: Position (Magenta) Vs Stair Input (Yellow)

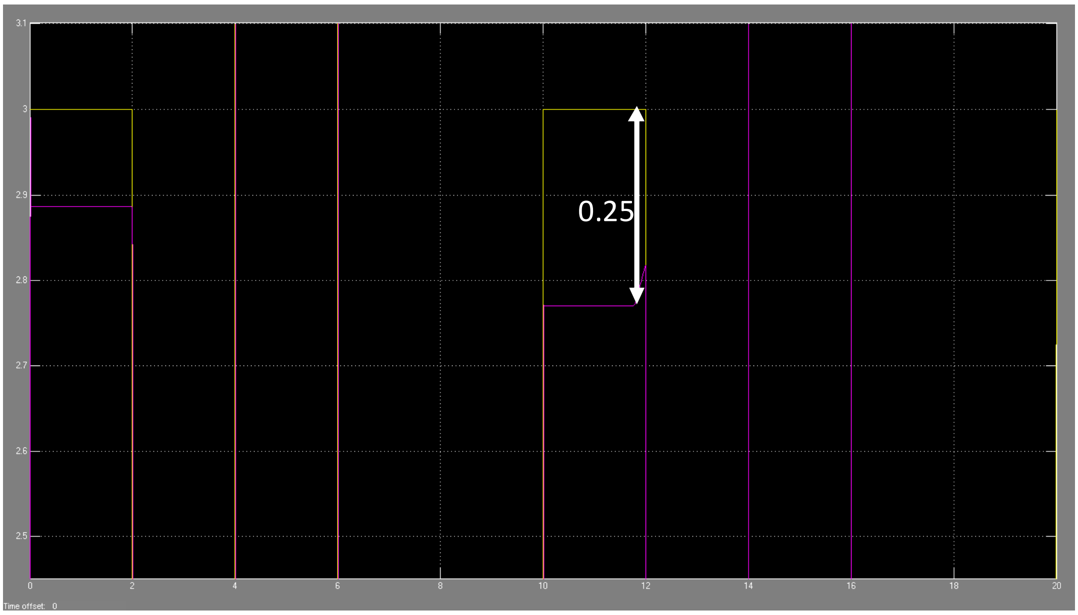


Figure 54: Motor Position (Magenta) Vs Stair Input (Yellow) - Zoom-In

7.6. SINE INPUT

- Amplitude = 5;
- Bias = 0;
- Frequency = 1 rad/sec; Phase = 0;

Actual motor position (magenta) and step input (yellow) are shown in the Figure 55:

Figure 55: Motor Position (Magenta) Vs Sine Input (Yellow)

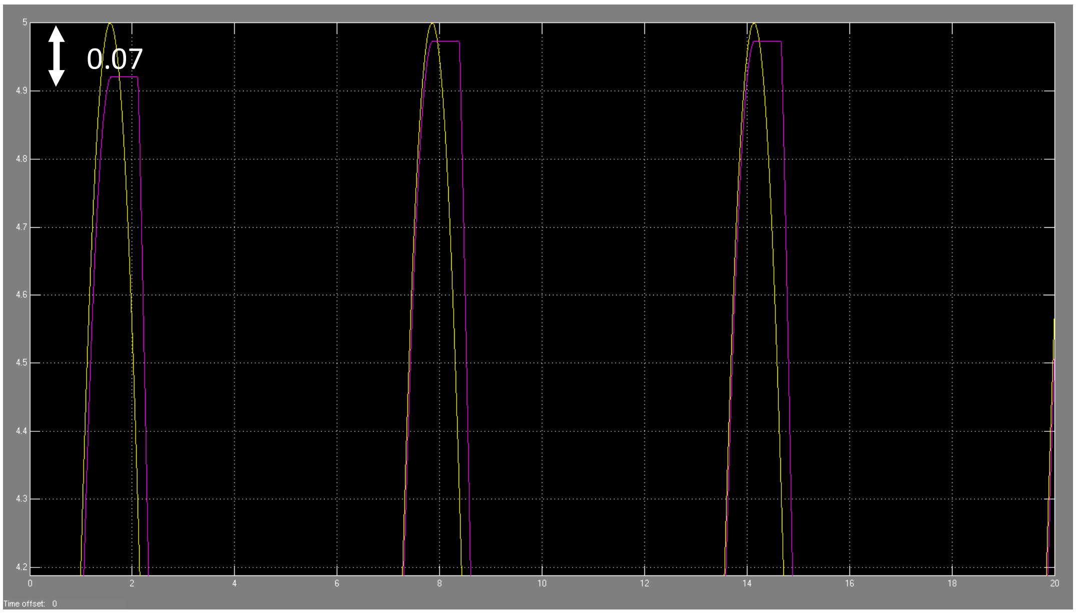


Figure 56: Motor Position (Magenta) Vs Sine Input (Yellow) - Zoom-In

7.7. RESULTS

Tests on EC motor with different input have been performed basically for three main objectives:

- check the DSPACE physical cabling, voltages level
- Matlab® SW connections;
- check if the configuration of the PID is reasonably correct;

In both objectives the results are good. In particular, no further adjustments have been needed in the DSPACE cabling. Matlab® output have been normalized to 1 (output within 0-1 range) in order to have the desired output on DSPACE I/O.
Regarding the PID configuration, some improvements could be implemented in order to reduce the steady position error in case of square input (worse situation).

8. Conclusions

The research crosses along brake by wire systems. The introduction of the such technologies is increasing safety and is making more comfortable vehicles use by the users. But the users still remain the focus point of such technologies. How they interact with people, correctly or not, define the utility, the acceptance and the effectiveness of such systems. For this reason, the research starts from the key point: the drivers. Braking process from the human factors point of view is analysed in chapter 0, detailing how literature describes step-by-step the braking action and how the users interact with the braking process. Some considerations could been done from the rationale so far, like the timing spent and the efforts done by the driver in order to apply the desired braking and the consequential output provided by vehicle to the driver on the brake, which informs the driver about the process status.

How the driver perceives the braking action from own point of view is a complex phenomenon. In particular, the braking perception, the so-called pedal feeling, is a physical sensation experienced as long as pedal is actuated by driver. It depends on several key parameters detailed in chapter 2 which has to, at least, take into account in the brake by wire design. A key role in the research is taken by the adaptability of the brake by wire: make it adaptable means modify dynamically its behaviours in function of external factor. In this case, the external factor is the scenario: different scenario leads to different brake behaviour: the criteria, the finding and the definition of the most important scenario are detailed based on the literature review and general consideration about vehicle uses. The listed use case try to cover all the potential case but it is out of discussion that they cannot include them all, especially for heterogeneous use of vehicles and drivers. Anyway, they are representative of major of the common day-by-day situations. Each use case has specific characteristics which lead to a specific pedal feelings which have been clustered within 4 principal behaviours. For each of them, as detailed in paragraph 3.6, the main characteristic which the pedal feelings is influenced of, pedal force feedback and deceleration needed, have been studied in function of what reviewed in the literature review. The results included in the chapter 4 are 4 behaviours defined by math functions of pedal force and deceleration needed, both depending on brake pedal travel. A consideration could be done about the discontinuities of the broken line of the graphs of the pedal force feedback: the sudden changing of the line inclination during the brake applying could create some doubts in the driver about the correctness of the pedal working. This is not a huge criticality in case of the applying pedal speed is high because the pedal pass through the vertexes very quickly. In case of the driver is applying incremental force on the brake pedal and it is slowly passing over a discontinuity, could feel the changing of the feedback and could be disoriented. For this reason, some interpolation could be introduced in order to make vertexes joined up. A linear filter could be enough.

Once defined how theoretically the pedal has to work, the research carried on software implementation on what described so far. A Matlab®/Simulink® model has been developed in order to firstly detect the use case in which the driver/vehicle is facing of (“Observer” module) and secondly to calculate the output (“AccCal” and “PedalControl” modules). Chapter 5 introduces the model logical flow, components, modules and deploy process. Starting from the literature, refinements and adjustments have been necessary in order to make concepts and theory correctly working on the software. In the end the model has been deployed and it ran on DSPACE

MicroAutoBox hardware. Once deployed, the model has been debugged hardware-in-the-loop via static input controlling firstly the single module and secondly the whole flow of the data. Considering the criticality and the quick changeability of the data regarding vehicle dynamic, it has been necessary to test the model with more realistic dynamic data. For this reason, it has been performed trials in order to collect real data on real vehicle on the road (chapter 6). The data collection has been carried out through custom ECU working jointly with a smartphone. A first trial has been focused on the adjustments of the data (like throttle release speed) because this type of data are very influenced by the vehicle characteristic (in this case, by throttle pedal return spring). This trials led to an adjustment of some variables which define the state identified by the "Observer" and it was very useful in order to make the validation more realistic. A second trial instead investigated each use case 3 times and relevant data have been stored in order to reproduce them as CAN logs. In this way, the model has received the logs recorded during the trials in a bench test. The "Observer" module, which takes care about the use case recognition, detected correctly the use case in the 92% of the case (22 on 24). For the 2 use cases not identified, the 2 entry state conditions of the "Observer" module has been slightly modified (acceleration threshold and positive road slope). Once corrected, the "Observer" detects all the 24 use cases. A special mention has to be done for a further log collected regarding mixed scenario, which includes casual use case the driver could find during a normal driving. The continuous changing of the scenario noticed in this type of log, could lead to a driver disorientation. The brake pedal feeling continuously changes in function of the scenario encountered. An improvement of the actuation logic could be introduced: for example, constant braking could be activated only if the road slope detected is present for a certain amount of time and not instantly (for example, downhill for at least 10 seconds). Another potential case in which the driver could be disoriented is the scenario changing while the driver is pressing the pedal. In this case, if the scenario has another reference curve regarding force feedback, a force change is not recommended. Keep the last use case seems to be the best way to proceed. For the case not analysed, which are not so common in the normal driving, the "Observer" could not find the right scenario: for this uncommon cases, one most conservative solution is to have the most responsive behaviour, which is the emergency one. The results on "Observer" debug and validation are positive: it is obviously limited to the case analysed and could be improved with other trials and following the considerations done so far.

In general debug and validation of the whole model have successfully been done: acceleration calculation ("AccCalc") and the control of the pedal ("PedalControl") modules work as expected. Some further debug has been performed introducing an EC motor in order to complete the loop. Once DSPACE cabling and Matlab® output has been checked, the motor has been activated with some reference set point in close-loop (encoder position feedback) controlled by a PID. Good results have been achieved (chapter 7).

Special mention for ADAS has to be done: ADAS are becoming important in the road safety and their presence are becoming usual in the standard vehicle. Especially, vehicle longitudinal control is even more influenced by systems like Automatic Braking and Adaptive Cruise Control. For this reason, a brake strategies like the ones described in this research must get ready for the ADAS introduction: in this case the vehicle is not equipped with ADAS, however, the implementation takes into consideration the availability (or not) of such systems like automatic parking system and information on the time to collision. In this way, selecting a vehicle with these systems, the strategies could be still adaptable.

The work thesis explored the field of the brake by wire, with a special focus on the human factors and driving involvement in the braking process. The role of the driver must not be under valuated because it is still the main responsible of the decisions taken during the driving: when, how much and with which modalities the driver and the vehicle interact during brake are still an important point.

9. Next steps

9.1. Driving Simulator Test & Experimental plan

Once developed the pedal mechanism (relevant patent are described in the following annex) methods and strategies defined in the this research could be tested with real users.
The experiment could be conducted in the driving simulator, which is shown in .
The selected driving simulator is an Oktal I-Drive SCANeR II system comprising a mock-up of an expected event with real driving controls (seat, steering wheel, pedals, gear, and handbrake) and a digital simulated dashboard displaying a traditional instrumental panel, with RPM, speedometer and vehicle subsystem lamps. More information on the Oktal I-drive SCANeR II can be found in 'Solution for driving Simulation: Application Programming Interface' by C. Courté (2007).
An hypothesis of experimental plan is provided in the following table. Based on 20 subjects, the drivers have to follow the guideline provided, driving in different scenario.

Use Cases	Examples of simulation scenarios
Emergency	The subject follows a car which suddenly brakes without notice, forcing the subject to brake abruptly and stop the vehicle.
Low Speed	Scenario with a sudden slow-and-go traffic that force the subject to maintain low speed. E.g. on the highway when you go into a queue, or the enter queue in a roundabout.
Costant	Scenario with constant downhill which requires the subject to prolonged use of the brake.
Adaptation	Traffic scenario in which the subject have to maintain a constant distance from the followed vehicle (the simulator could suggest the right distance highlighting on the screen with a code, eg. Red = wrong distance, green = right distance).

TABLE 8: SIMULATOR TESTS EXPERIMENTAL PLAN

FIGURE 57: DRIVING SIMULATOR

10. Annex 1: the design of brake pedals - materials and ratio

A Human Factor principle in vehicle design states control levers must move in the direction in which the operator's limbs naturally move and thereby limbs exert their force. There must be considered also a zone in the arc of travel of any limb in which the operator can exert force effort with the greatest efficiency All control levers, including pedals, should be designed so that they can move and transmit the operator's force through that zone. Operator's knees should be comfortably bent, so that he can ideally straighten one knee toward what is called the "extended leg" (Hertzberg , Burkei, 1971). Two other factors affect the magnitude of the forces the driver can exert on the brake pedal:

- the size (mainly the length) of foot;
- the position of the foot on the pedal as force is usually provided by the ball of the foot.

Material

The pedal boxes on the market are currently made of materials ranging from metal to polymers. There is much research in the area of creating pedals and other automobile components made of composites in order to increase the strength of the pedal and at the same time decreasing the weight. Composites also tend to provide material benefits as high stiffness and corrosion resistance (Sapuan 2011). The decreased weight of the components can help designer to improve greening a savings in the area of fuel consumption for vehicles.

Ratio

The pedal ratio is the most important design factor on the “feel” of traditional brake pedals. Depending on the setup of the hydraulic cylinders with respect to the rotation of the pedal, the pedal ratio can be calculated differently. However, for forward mounted horizontal hydraulic cylinders the calculations for the pedal ratio and resulting force is based on simple geometry (Scheitlin, 2011). The pedal ratio is the overall pedal length or distance from the pedal pivot called the fulcrum to centre of the pad your foot will push against (L1+L2) divided by the distance from to the fulcrum to the master cylinder push rod attachment point (L1).

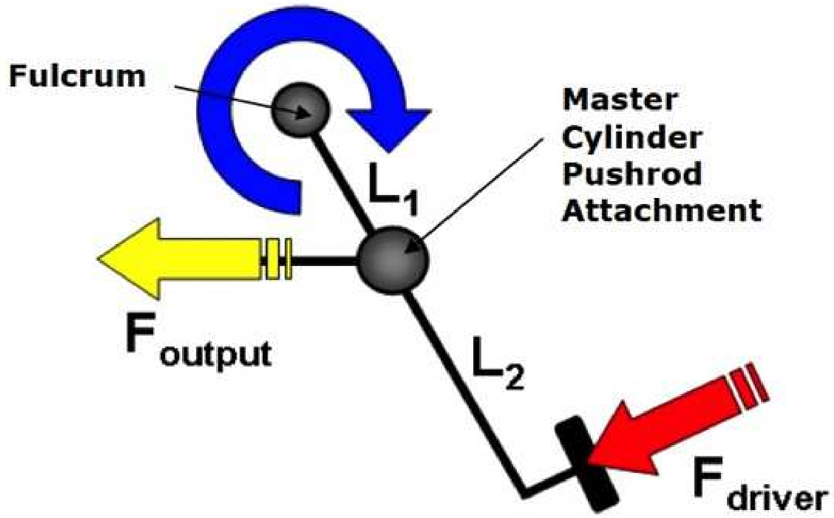


Figure 58: Traditional Brake Pedal Force Outline

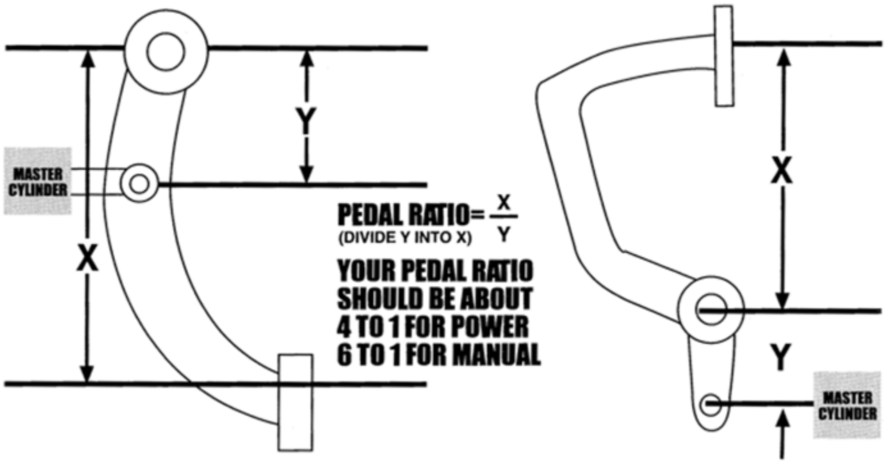


Figure 59: Calculation Of The Pedal Ratio

By increasing the pedal ratio, the actual force applied to the cylinders and therefore the braking system would increase. For typical manual brake systems, the pedal ratio is between 5:1 and 6.5:1, but for power systems a typical ratio of 4:1 to 5:1 is more likely to be seen due to the force conversion relationship (Oshiro, 2010). Factory cars generally have two pedal ratios, one for manual brakes and one for power brakes. You will find manual pedals with ratios from 5:1 to 6.5:1 and power pedals 4:1 to 5:1.
Experience has shown that a pedal ratio of 6.2:1 is recommended to replace most of the brake force assist that was provided originally by the vacuum assist and the original equipment pedal ratio of 3.5 to 4.0:1. This means that you cannot usually reuse the original equipment pedal to build a pedal arrangement with dual master cylinders because the stock pedal is simply not long enough and often the fulcrum is too low to the floor to provide enough room to make the brake

pedal longer. Shortening the distance from the fulcrum to the pushrod would have the same effect, but is a difficult task best left to an expert fabricator.
Having a higher pedal ratio would increase the effectiveness of the applied force, but it typically would also require a higher pedal travel and poor brake feel (Yabusaki, 2011).

Example of variable ratio brake pedal

A brake pedal with variable ratio has been designed and developed in order to provide the driver with a less aggressive brake feel (Mok, 2007). In most cases, the OEM will initially model the brake system with a pedal having a constant geometric ratio. OEM typically define the model basing on regulations, for instance the requirements of USA FMVSS 135 that stipulates brake performance in the event of “brake power assist unit inoperative” (i.e. no assist from any of the “powered” components of the brake system as brake booster, master cylinder, etc.). This implies that all the braking effort will then be generated solely by the mechanical ratio of the pedal also states that with an applied force at the pedal pad of no more than 500N, the vehicle must stop within 168m, at a test speed of 100km/h.
Based on this known load at the pedal pad specified by the test and the provided traditional geometric ratio, it could be possible then calculate the amount of force transmitted to the brake booster for this panic braking scenario and plot an instantaneous ratio curve (i.e. pedal ratio vs. booster travel), this point is then known as the critical point of the curve. In a conventional fixed ratio pedal, the instantaneous ratio will continue to increase after the critical point. When designing a variable ratio pedal, however, the goal is to maintain the desired ratio at the critical point such that the instantaneous ratio drops after that point. This will result in a pedal that meets both the regulatory criteria as well as the OEM’s subjective feel requirements.

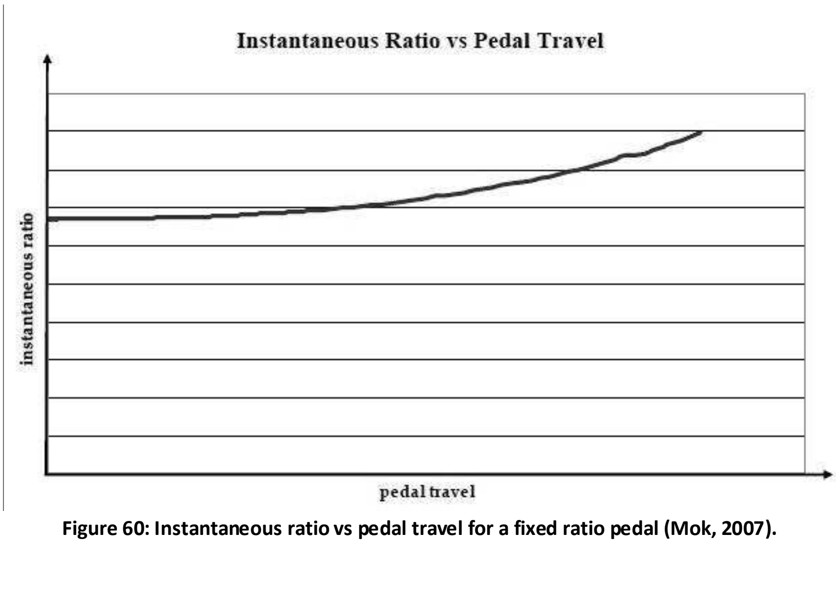


Figure 60: Instantaneous ratio vs pedal travel for a fixed ratio pedal (Mok, 2007).

From the graph, it is apparent that as pedal travel increases, the slope of the curve increases. This increase in slope corresponds to an increase in the rate of change in the instantaneous ratio. In other words, for a constant input force, the increment at which the output force increases becomes larger as pedal travel increases.

This “accelerating” pedal ratio will cause the driver to be more inclined to propel forward as the brakes are applied, which can be displeasing for the driver and any passengers in the vehicle. By contrast, the variable ratio pedal is designed to give the driver a less aggressive brake feel by decreasing the rate of change of the instantaneous ratio with pedal travel (Mok, 2007).

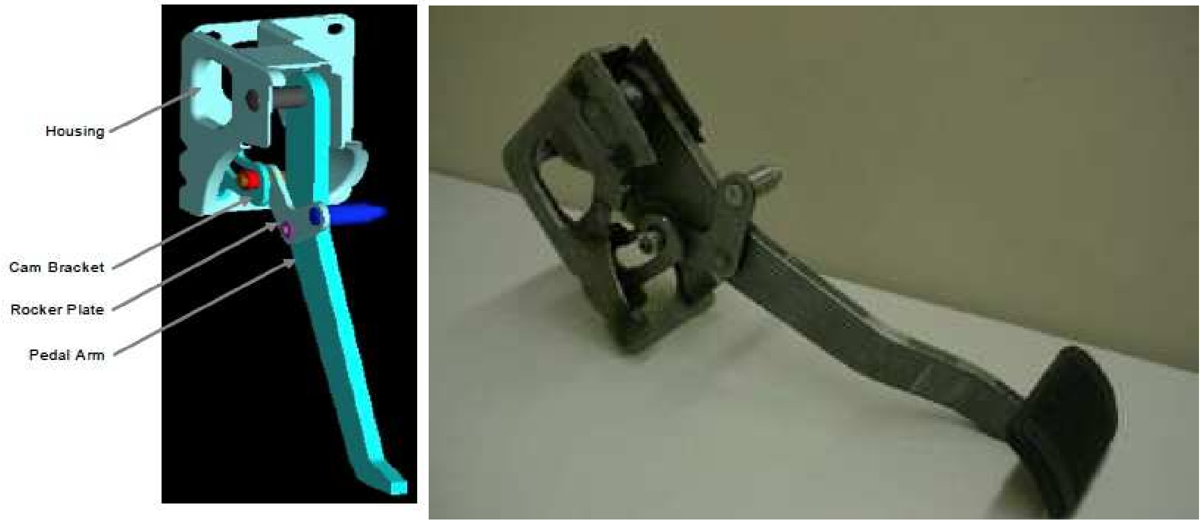


Figure 61: 3d Model And Final Assembly Of Variable Ratio Concept Brake Pedal (Mok, 2007)

11. Annex 2: Brake by wire pedal design hypotheses and review of patented technologies

11.1. General remarks

Several technology can be developed and deployed about Brake-by-wire actuator and feeling simulator. In particular the brake pedal geometry and the related input/output interface with user can be developed starting from different morphological concepts. For instance type of sensors involved in design and the physical and mechanical way to provide force feedback impact a lot on the definition of technical specification and further development. Potential identified technologies to be developed need to be evaluated according to requirements and their chance to be suitable for the project objective. Evaluation criteria impact on the final choice of technology.

List of potential technology evaluation criteria:

- overall pertinence with general requirements;
- ergonomic suitability for user and for the task;
- general mechanical suitability for the task (e.g. geometry, durability, etc.);
- sensor type, integration and suitability for the task;
- force feeling feedback and potential regulations;
- technical feasibility;
- maturity of technology;
- potential future improvements;
- dead band of actuator;
- technology related fault tolerant aspects
- industrial and concept related costs;
- regulation compliant;

As example of technology evaluation in brake by wire design and development, the Challenge X research study evaluated five concepts (Pan, 2007). From these five concepts, some were too expensive to produce and others would not be durable enough to withstand the force on the brake pedal. The concept of maintaining the stock dead band was incorporated into all of the other concepts. Another main concept principle was which type of sensor to choose. The options for types of sensors were: linear, angular, or rotational. The angular and rotational sensors can be mounted to the bracket or rotating pedal without involving much work. These sensors will cost a great deal more than the linear sensor, which ruled them out as viable options for the brake pedal design. The last main decision, which needed to be made by Challenge X research team, was how to attach the sensor to the pedal. Final concepts were put into a Pugh chart to weigh how the customer needs would be fulfilled by each of the concepts according to defined criteria. Through

the Pugh chart Challenge X research team could rate the concepts and decide which one would be the best to produce (Pan, 2007).
The five concepts evaluated by Challenge to X research were:

- Mount sensor to pedal and back bracket with a four-bar linkage;
- Mount sensor to pedal and back bracket directly;
- Mount sensor to pedal and additional top plate;
- Mount angular sensor to pedal and back bracket directly;
- Mount rotational sensor to pedal and back bracket directly.

The first one (i.e. Mount sensor to pedal and back bracket with a four-bar linkage) was selected and developed.

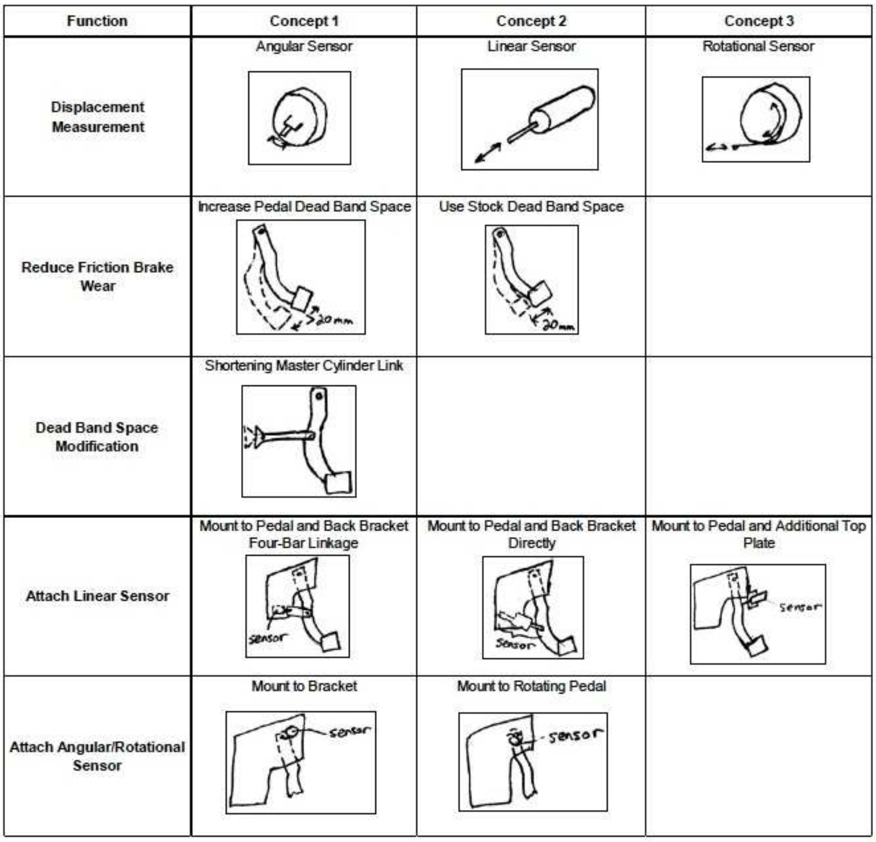


Figure 62: Example Of Morphological Chart For Brake-By-Wire Pedal Design (Pan, 2007)

		Concepts									
		Mount sensor to pedal and back bracket with a four-bar linkage		Mount sensor to pedal and back bracket directly		Mount sensor to pedal and additional top plate		Mount angular sensor to pedal and back bracket directly		Mount rotaional sensor to pedal and back bracket directly	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Pedal position similar to stock vehicle	0.08696	5	0.4347826	5	0.4347826	5	0.4347826	5	0.4347826	5	0.4347826
Brake application similar to stock vehicle	0.08696	5	0.4347826	5	0.4347826	5	0.4347826	5	0.4347826	5	0.4347826
System is durable	0.15217	4	0.6086957	3	0.4565217	4	0.6086957	4	0.6086957	4	0.6086957
System sensors integration	0.17391	5	0.8695652	5	0.8695652	5	0.8695652	5	0.8695652	5	0.8695652
System meets all regulations	0.19565	5	0.9782609	5	0.9782609	5	0.9782609	5	0.9782609	5	0.9782609
Low prototype cost	0.06522	4	0.2608696	4	0.2608696	4	0.2608696	2	0.1304348	2	0.1304348
Low production cost	0.04348	3	0.1304348	4	0.173913	3	0.1304348	2	0.0869565	2	0.0869565
Driver ergonomics	0.1087	4	0.4347826	4	0.4347826	4	0.4347826	4	0.4347826	4	0.4347826
Manufacturability	0.08696	4	0.3478261	4	0.3478261	3	0.2608696	4	0.3478261	4	0.3478261
	Total Score	4.5		4.391304348		4.413043478		4.326086957		4.326086957	
	Rank	1		3		2		4		4	

Figure 63: Example Of Pugh Table For Brake-By-Wire Technology Evaluation (Pan, 2007)

11.2. Review of relevant patents

In current State of the Art analysis, 24 relevant patents have been identified about technology impacting on electronic braking actuator and Brake by wire system development.
They have been presented by relevant OEMs for automotive industry as Continental, Bosch, Delphi and Advics, by vehicle manufacturer as Ford, Hyundai and GM and also by private individual often as partner of industries.

Table 9: List Of Relevant Patents About Brake By Wire Technology

Patent Code	Short patent title	Author	Year	Family
US6267208	Pedal-Travel-Simulator	Bosch	2001	Sensors
US6309031	Vehicle-brake-system-with-variable-brake-pedal-feel	Ford	2001	System
US6367886	Brake-Pedal-Emulator-System-And-Method	Delphi	2002	Feeling simulator
US6662906	System-Of-Controlling-Or-Regulating-An-Electromechanical-Brake	Continental	2003	
US6918466	Lockable-brake-pedal-fastener	Hopkins	2005	
US7219966	Brake-Pedal-Feel-Simulator	Continental	2007	Feeling simulator
US7357465	Brake-Pedal-Feel-Simulator	Continental	2008	Feeling

				simulator
US8038227	Brake-Control-Device-Improving-Drivers-Brake-Feeling	Advics	2011	System
US20020108463	Magneto-Rheological-Brake-Pedal-Feel-Emulator	Delphi	2002	Feeling simulator
US20020117893	Brake-Pedal-Feel-Emulator-With-Integral-Force-And-Travel-Sensors	Delphi	2002	Feeling simulator
US20050057096	Brake-Control-Device-Improving-Drivers-Brake-Feeling	Posz-Bethards	2002	
US20050082909	Pedal-Feel-Emulator-Mechanism-For-Brake-by-Wire-Pedal	Constantakis	2005	Feeling simulator
US20060071545	Brake-Pedal-Feel-Simulator	Continental	2006	Feeling simulator
US20060278033	Brake-Pedal-Device	Kanesaka-Berner	2006	
US20070296268	Piezoelectric-composite-brake-pedal-feel-emulating-system	Thompson-Hine	2007	
US20080229868	Brake-Pedal-Device-For-Effecting-Service-Braking-Lock-Braking	Ladas-Parry	2008	Pedals
US20110113874	Brake-Pedal-Stroke-Sensor_Hyundai_2011	Hyundai	2011	Sensors
US20110130935	Methods-And-Systems-For-Brake-Pedal-Tuning-Braking-Control-In-Vehicles	GM	2011	System
US20110203405	Brake pedal stop_Bendix-CVS_2011	Bendix-CVS	2011	
US20110107870	Pedal-Apparatus-frp-eòectric-motorcar-or-for-motor-vehicle-having-throttle-mechanism	Naruse	2011	Pedals
US2003122418	Motor-driven feedback mechanism	Stachowsky, Pavlov, Stevenson	2003	
US6591710	Single cantilever spring pedal feel emulator	Delphi	2003	Feeling simulator
US2008217122	Brake-actuation unit for actuation of a motor vehicle braking system	Continental	2008	
US2007138863	Modular Pedal Box Assembly	Clark et al.	2007	Pedals

The reported patents refer mainly to four "families" of concepts:

- **electro and mechanical physical pedal concept** - patents related to specific pedal design, describing in details geometry and mechanical aspects of the proposed design solution.
- **sensors** - patents related to pedal sensors to detect specific aspect of the users movement or of force feedback. Typically they deal with pedal travel or forces.

- **brake pedal feeling simulator and emulators** - overall solution including pedal geometry, sensors and active force feedback mechanism. Typically they focus on adjustable or pre-set force feedback technology
- **advance complex systems involving sensors and ADAS** - complex design solution involving extra brake system sensors and equipment.

Some of them, as Continental's patents, report a progressive evolution of concept in order to define better and better a brake feeling technology.
The patent described so far could be collected inside some families:

- **Pedals:**
    - Modular pedal box assembly
    - Brake pedal device for effecting service braking
    - Lock braking
- **Sensors:**
    - Pedal stroke sensor
    - Pedal travel simulator
- **Pedal feel simulators:**
    - Brake pedal simulator
    - Brake pedal feel emulator
    - Motor driven feedback
- **Systems**
    - Brake system with adjustable brake pedal feel
    - Methods and systems for brake pedal tuning

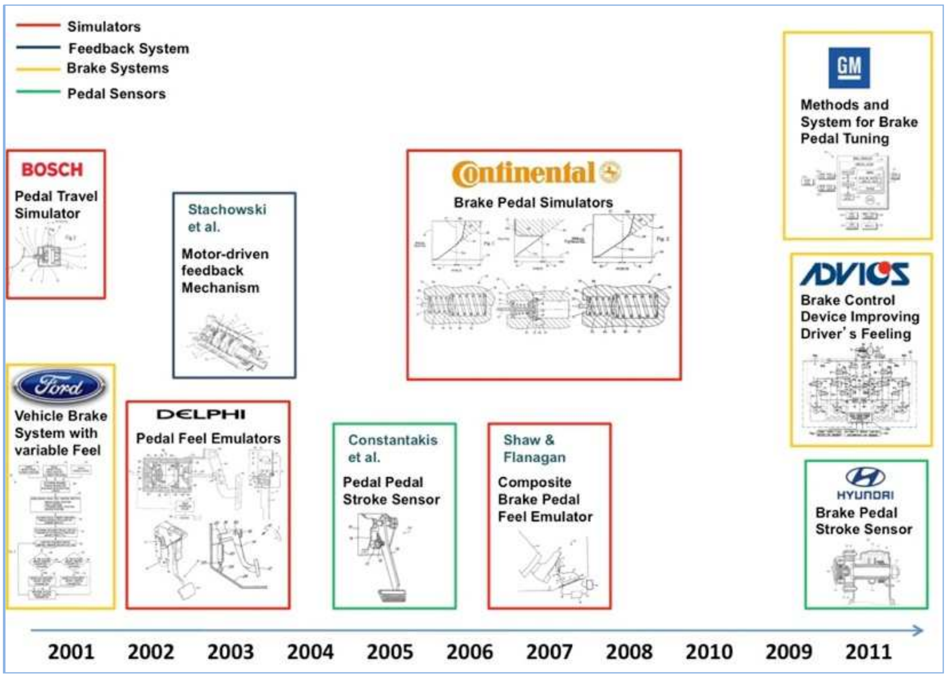


Figure 64: Relevant Patent Timeline

11.3. Alternative pedal design solutions

The most relevant design solutions about active pedal and brake by wire system are reported in this section. They came out investigating technologies from concepts and patents and represent different development and deployment of brake by wire in order to provide users an active brake feeling. They mainly differ each other by the technology adopted to set, adjust and provide the force feedback. The actuation type and movement required to the users is not under evaluation as all these technology adopt leg- and ankle-operated pedals.
Four types of active pedals are briefly presented:

- linear sensor, spring and rubber;
- motor-driven feedback solution;
- magneto-rheological brake design;
- other design solution.

11.3.1. Linear sensor, spring and rubber design solution

Basing on existing pedal geometry and mechanism, some pedal design involve a linear sensor to detect the stroke or pedal travel. Some concepts derived from this design solution are briefly presented below.
The required force, the pedal feeling and feedback are provided by mechanical resistance from the pedal. Most common solution involved an horizontal cylinder placed behind the pedal leverage. This cylinder represent the "pedal simulator" as it provide the force feedback directly to the pedal. These design solution aim at set and simulate several force feedback and pedal feeling according to users' needs (Continental) setting the rubber stiffness and spring resistance by software.

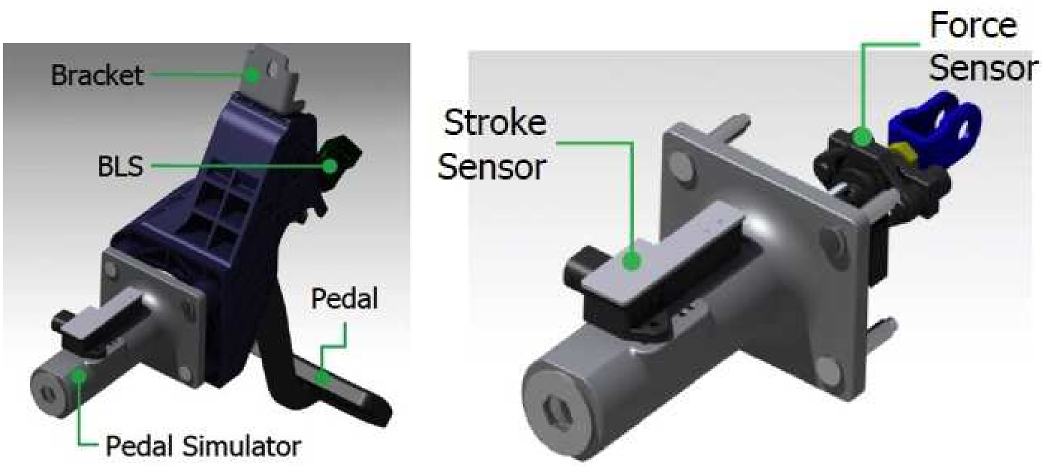


Figure 65: Pedal simulator : brake feel tuning by software (Cheon et al., 2010)

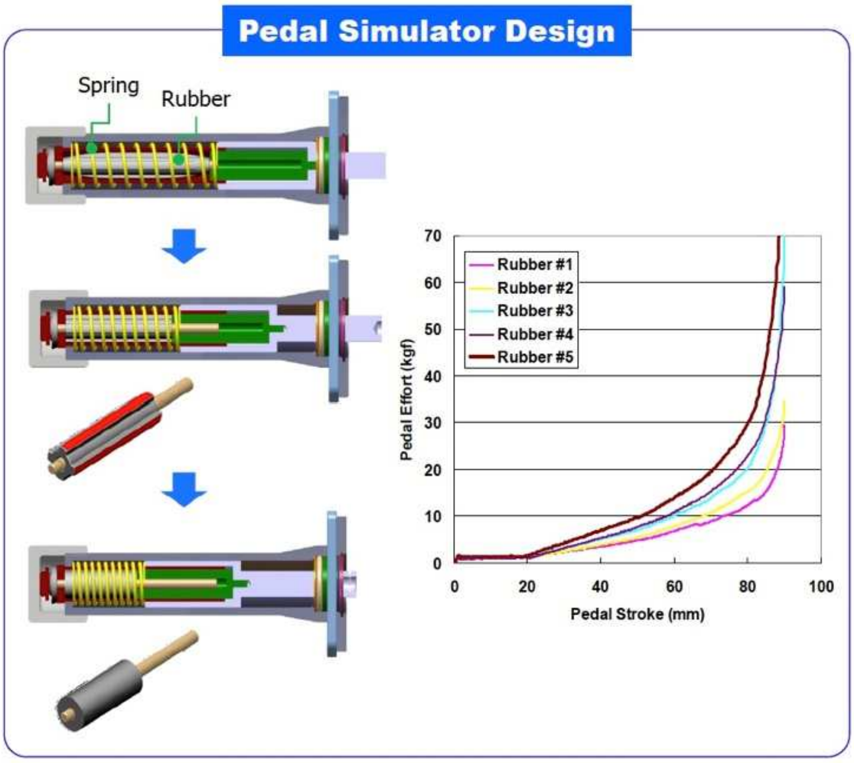


Figure 66: Pedal simulator design - rubber types and effort (Cheon et al., 2010)

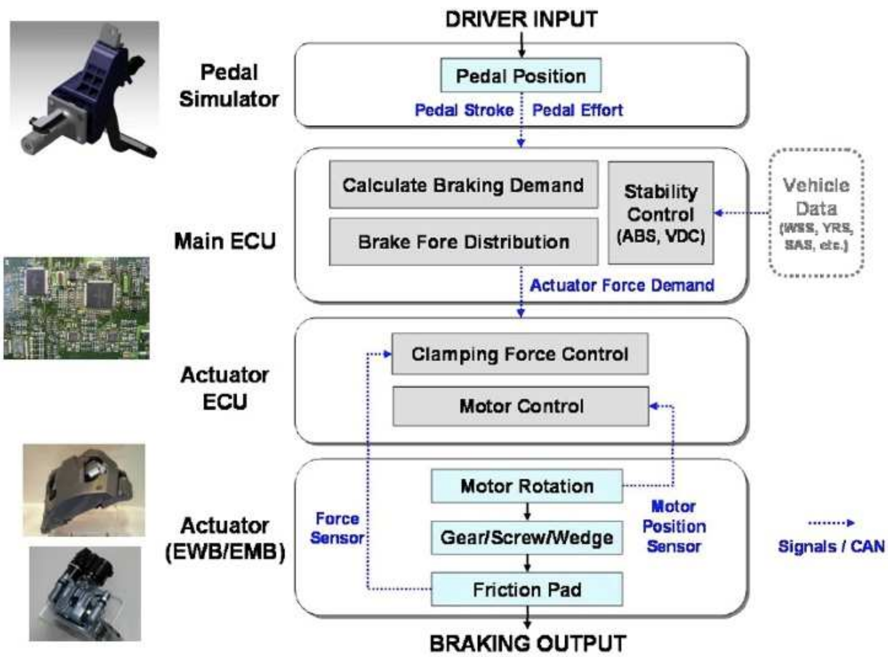


Figure 67: Example of software design architecture (Cheon et al., 2010)

The following picture reports a detail from one of Continental's patents. This pedal feel simulator comprises two separated springs with different spring rates. When a pre-determined force level is achieved at brake pedal and simulator, the spring rate provided by the simulator shifts to the second spring rate. The rate resistance to translation of brake pedal is reduced, improving the operator's ability to brake the vehicle.

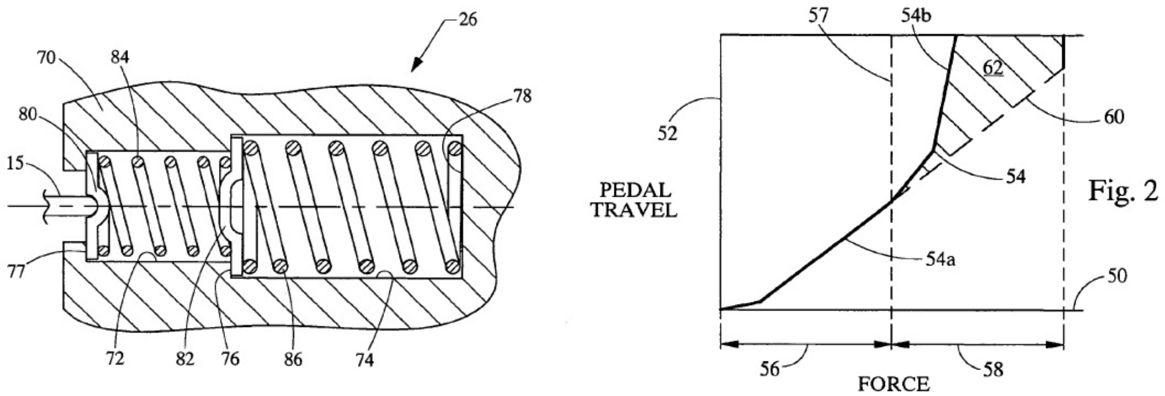


Figure 68: Springs/Rubber Feeling Simulator Concept (Continental Patent US20060071545)

The overall goal of the Delphi project was the design of a new electro-mechanical braking based on time-triggered communication. The activities led to the development of a prototype based on a current series car model. A central processor provided supervisory control and a pedal feel emulator driver feedback. Main benefits included the near elimination of the residual torque between brake pads and disks, a more accurate response to driver commands and an easier integration with vehicle dynamic control systems.

Figure 69: TTTTECH And Delphi Concept For Braking Pedal Module

Another concept of brake-by-wire pedal was developed under the project Challenge X (Pan, 2007). The research team developed a pedal with linear sensor in order to get mainly data about pedal travel.

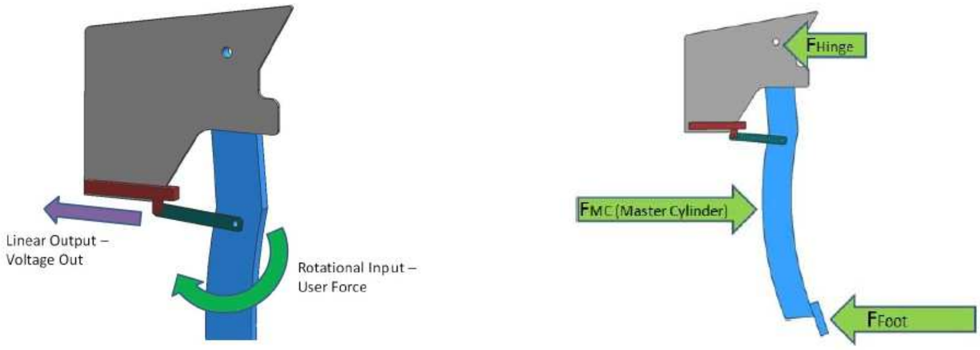


Figure 70: Mount sensor to pedal and back bracket with a four-bar linkage (Pan, 2007).

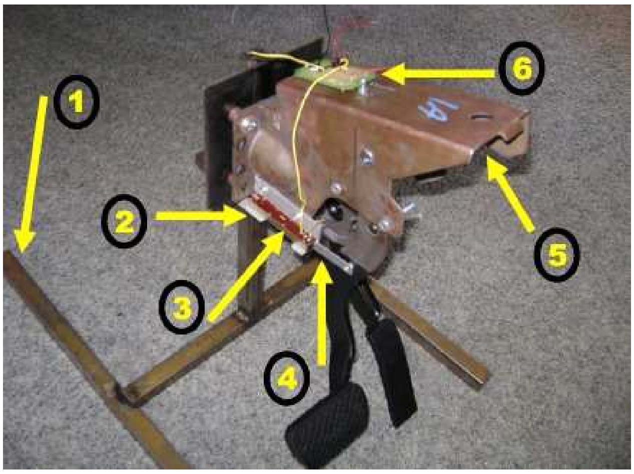


Figure 71: Linear sensor brake by wire pedal concept (Pan, 2007).

11.3.2. Rotating motor-driven solution

This type of design solution provide the force feedback to the pedal through direct mechanical connection between pedal and an electric motor. The motor device provides one rotary active degree of freedom in the direction of the leg and ankle movements.
The following figures present motor-driven throttle with active feedback. The motor is able to provide programmable torques.

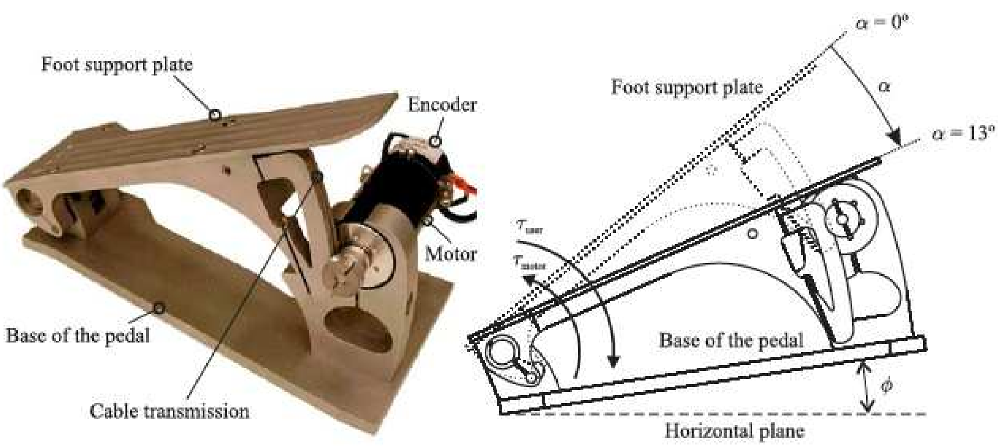


Figure 72: Motor driven force feedback in haptic accelerator pedal (De Rosario et al., 2010)

The following figures present another patent about motor-driven feedback mechanism for a braking pedal (Stachowsky, 2003). In this concept the pedal is linked to a shaft and a bi-directional motor capable of operating in a first and a second direction is linked to the shaft. A microcontroller and a microprocessor are able to control the motor to provide the programmed force feedback to the brake pedal.

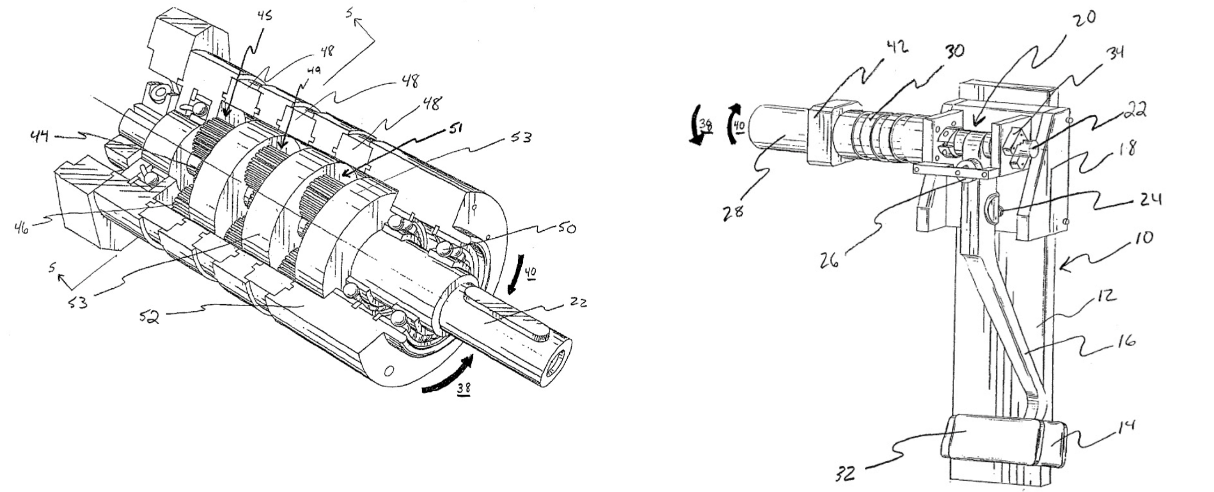


Figure 73: Brake pedal driven by motor (Stachowsky et al. Patent US20030122418)

11.3.3. Magneto-rheological brake design

The magneto-rheological technology allows to emulate the brake pedal force feedback and feeling. This patent from Delphi includes a housing defining a fluid chamber containing a magneto-rheological fluid. A piston is slide-ably disposed within the piston chamber and a spring biases the piston to resist depression of the brake pedal. A magnetic source generate a magnetic field upon the fluid emulating the force feedback. The amount of resistance can be varied according to the strength of the magnetic field exerted on the fluid.

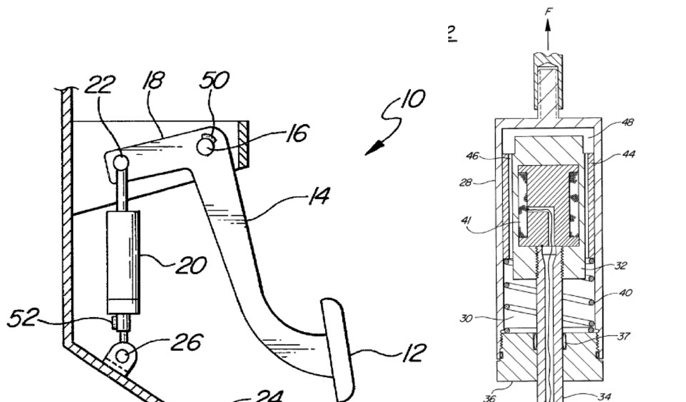


Figure 74: Magneto-Rheological Brake Pedal Feel Emulator (Delphi Patent US20020108463)

Another concept involving magneto-rheological technology consists of rotating disks immersed in a magnetic fluid and enclosed in an electromagnet, which the yield stress of the fluid varies as a function of the magnetic field applied by the electromagnet. The controllable yield stress causes friction on the rotating disk surfaces, thus generating a retarding brake torque. The braking torque can be precisely controlled by changing the current applied to the electromagnet (Park et al. 2006).

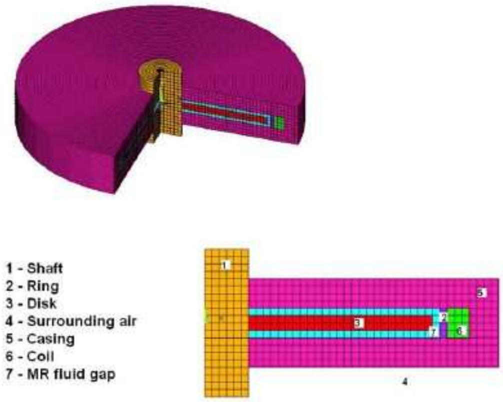


Figure 75: Basic configuration of a magneto-rheological brake concept (Park et al., 2006)

11.3.4. Other design solution

Some alternative arrangements of pedals have been studied and proposed such as combination of brake and accelerator pedals. Example of the alternative design solutions are the so called "drag-alone" brake pedal, the translation-rotation pedal or the "Naruse" pedal. There also plans to do away with pedals and control longitudinal vehicle movement by joysticks operated either by left or right hand.

The "Naruse" pedal has not been designed to brake by wire specifically but it represents an interesting case of pedal integration. It is a brake pedal having an accelerator pad configured to be rotated in the lateral direction within a pre-determined angle range for an accelerating operation.

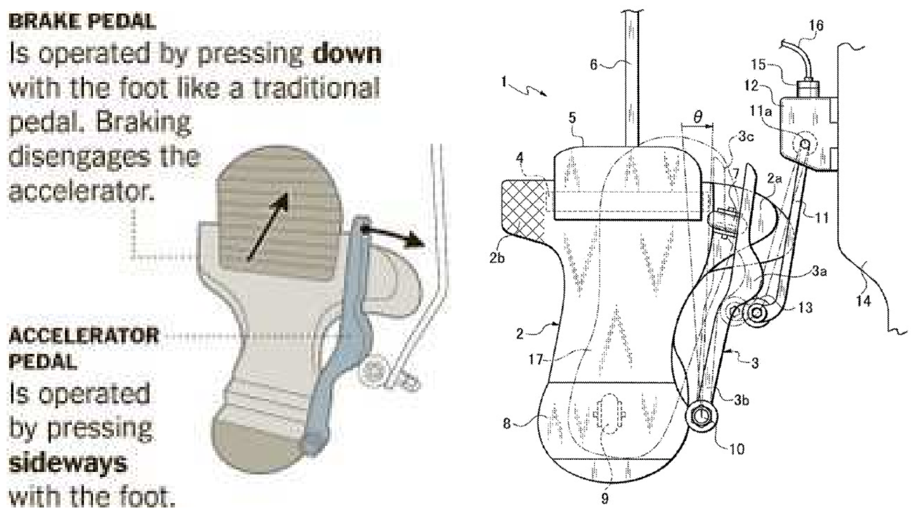


Figure 76: "Naruse" Pedal (Naruse Patent, US20110107870)

Table 10: Review of emerging brake technologies (Winkler, 2005).

Technology	Objective technical Description	Qualitative Engineering Assessment	Likelihood of Commercial introduction
Electronic brake-by-wire (General consideration)	A braking system in which the primary action of the driver's control device (to date, the brake pedal, but potentially other devices) is to modulate an electrical signal. The control may incorporate additional mechanical action for fault protection, and force feedback for driveability.	Provides a flexible control interface that is especially appropriate for braking systems with advanced functionalities. Also reduces reliance on hydraulic components and offers greater flexibility in vehicle packaging and assembly. Some form of transducer redundancy at the brake pedal is necessary for overall fail-safe protection of the braking system. Includes electro-hydraulic and electro-mechanical braking systems.	Currently in production. It is estimated it will become a significant technology.
Electro-hydraulic braking system (EHB)	Particular form of brake-by-wire system. Uses electronic sensing from the brake pedal to control hydraulic valves, connecting to conventional hydraulic actuators at the road wheels.	Allows control of individual wheel cylinders to optimize braking performance and reduce stopping distances. Can be designed to incorporate fully hydraulic backup system in the event of electronic system failure (and requires a fault diagnosis and isolation function to trigger the backup system). Especially useful as a platform for higher level braking system functions such as ABS, ESB and crash mitigation	Already in commercial production with Mercedes-Benz (E-class and CLS-class), but likely to be a 'hybrid' between conventional hydraulic and electro-mechanical brake-by-wire.
Electro-mechanical braking system (EMB)	Particular form of brake-by-wire system that uses electro-magnetic actuators to directly control the friction forces at the road wheels	Has all the performance and flexibility benefits of electro-hydraulic braking systems. It offers additional benefits for system integration (e.g. electric parking brake capability). There is no mechanical backup system, thus system redundancy and fault tolerance aspects are key factors for the safe introduction of this type of system.	Supposed it will be. Major brake system suppliers are demonstrating prototype products. The range of advantages of EMB appear overwhelming.
Fault tolerant by-wire braking systems	An advanced system level concept for full electronic by-wire braking system, where no mechanical backup is available.	By-wire braking is the most safety critical system being proposed for full electronic control on vehicles. No independent system would be available to compensate for the failure of a fully electronic by wire braking system. Therefore new fault tolerant systems must be developed that deliver proven levels of reliability and fault tolerance. Particularly significant in that the existence and performance of this type of system is almost entirely hidden within the electronic architecture of the vehicle.	An essential aspect of by-wire braking systems. Introduction almost certain.
Regenerative electric braking	A system that under braking converts some of the vehicle's kinetic energy into electrical energy. Uses an electrical machine to generate eclectic current and either battery or ultra capacitor to store charge.	This system has real benefits for improving fuel economy, but is limited by the need for powerful electrical machines and power storage. This means the technology is not a practical add-on to existing vehicle power trains and is restricted to being used within a hybrid or mild hybrid electric power train where a suitable high-voltage electrical	Already deployed in the Toyota Prius, Honda Insight and Chevrolet Silverado hybrid vehicles.

		system is already in place (e.g. 42 volt Integrated systems).	
Regenerative hydraulic braking	Hydraulic regenerative braking recovers energy and stores it as high-pressure hydraulic fluid in an accumulator.	With a similar function to electric regenerative braking, in this system a hydraulic motor is coupled to the vehicle drive train; under vehicle braking the hydraulic motor pressurizes an accumulator, storing some of the vehicle's kinetic energy which is utilized for 'launch assist', reducing the energy requirement for subsequent acceleration. The system is suitable as an adaptation to existing power trains and an economic investment for fleets of light delivery trucks, taxis and buses. Offers little benefit for drive cycles that only include rare stops.	Commercial introduction is likely in niche vehicle sectors such as urban delivery trucks. Currently being developed by Ford and Eaton for the F350 concept truck, the technology is relatively mature and of low technical risk.
Magneto-rheological brake actuator	Braking torque generated by shear forces in a magneto-rheological (MR) fluid controlled by an applied magnetic field.	This type of brake actuator uses a fluid as a the friction medium. The technology is proven for relatively low power density applications such as automotive suspension dampers, and controllable brakes for exercise machines. The critical performance characteristic for automotive braking applications is thermal management and high temperature behaviour of the MR fluid. It offers significant advantages in terms of improved brake torque control and being environmentally friendly.	It is not a 'front runner' technology at present, but might become attractive if introduced in combination with other novel braking concepts - for example as a backup safety system for high capacity regenerative braking systems.
Piezo-electric brake actuator	Piezo-electric elements are used to generate hydraulic pressure at each wheel; hydraulic pressure is maintained in one or more accumulators at each wheel, and brake torque is controlled via a conventional solenoid valve.	Piezo-electric actuators are becoming increasingly common, for example in diesel fuel injection systems. They are not appropriate for direct actuation of disk pads, but coupled to a hydraulic system as a novel electrical pump, the concept is feasible. Advantages are simplicity and high reliability of piezo-electric actuators, compatibility with brake-by-wire concepts, and compatibility with standard disk and caliper components.	Technology may be attractive for brake-by-wire applications. The system is currently being researched. The likelihood of commercial introduction is currently low.
Electronic Brake Assist (EBA)	Electronic system that incorporates estimation of driver intention, to recognize emergency brake application, and in this case increase brake system gain and or response speed.	The system is effective in overcoming the common reluctance of drivers to apply full braking effort, even in the case of an emergency situation. The system detects rapid brake pedal action to initiate the brake assist. It is clearly capable of reducing braking distances in these situations. Because of the flexibility of the system, it is capable of adapting to different driving styles, and can be combined with other systems such as crash mitigation and collision avoidance.	This type of system has been in commercial existence for several years. First introduced by Mercedes-Benz (supplier Continental), a number of car companies are now looking at implementing such a system.

Mechanical Brake Assist (MBA)	Mechanical system that performs an identical function to EBA.	A cheaper alternative to EBA, the system uses a mechanical valve that responds to rapid pedal acceleration. This additional valve then triggers a rapid and increased braking system response. The device characteristics are fixed, and so this system lacks any possibility to be incorporated within an intelligent braking system, such as ESP, Crash Mitigation or Collision Avoidance.	As a lower cost system than EBA, may fill a market gap during next years. But is unlikely to gain a long term market acceptance.
Crash Mitigation System	System that detects impacts, e.g. using RADAR, may progressively warn the driver of a frontal crash and apply moderate braking effort (e.g. up to 0.3g deceleration) and finally apply maximum braking when impact appears inevitable.	This type of system may take partial control of the vehicle when a crash appears imminent. It may pre-deploy restraint systems and air bags/curtains, but of greatest relevance here is that partial or full braking will be deployed, independent of any driver decision. The concept is simply that a crash is inevitable, and that reducing vehicle speed will mitigate the effects.	This type of system is very likely to be deployed in the US market. It is commercially available in Japan (by Honda) and is under prototype development at Ford. Bosch and Delphi have also published papers indicating their interest in the area.
Collision Avoidance System	A collision avoidance system may support, warn or override the driver in an attempt to avoid a collision. Of relevance here is any sub-function that automatically deploys the brakes as part of the overall collision avoidance strategy.	This is any collision avoidance system that automatically applies the brakes to achieve this - as such, the system requires significant sensor data and signal processing to establish sufficient situational awareness to justify taking control away from the driver. Experience with collision warning systems indicates that precise situational awareness is not easily established from existing vehicle sensors.	Only likely if crash warning systems are seen be ineffective in the field, and crash fatality rates are not amenable to other measures. The main inhibitory factor in the USA is likely to be fear of adverse litigation.
Vehicle Stability Control (VSC).	Single wheel braking is automatically triggered as a countermeasure for over steer or under steer.	This system, also known as Electronic Stability Program (ESP) uses a yaw rate sensing and sideslip estimation to compare with a reference vehicle model - where large discrepancies are found, brake application is applied to restore desired (reference) vehicle behaviour. The primary purpose of brake actuation is to change vehicle rotation. Reducing vehicle speed is a side-effect of the system.	Although the system is already available, there is continued scope for wider market penetration and greater system functionality, such as integration with crash mitigation and avoidance systems.

12. Annex 3: Brake by wire pedal reaction times and braking behavior: example from an experimental researches

The following braking characteristics were analysed in the study performed by Fitch in 2010 (Fitch et al., 2010a): corrected stopping distance, perception time, movement time, stopping time, average deceleration, time to maximum pedal displacement, and maximum pedal force. Corrected stopping distance (distance) was measured as the distance travelled by the vehicle from the initial brake pedal application to the vehicle coming to a complete stop. Distance was corrected using the manoeuvre entry speed as specified in SAE J299 (Society of Automotive Engineers, 1993). Perception time (PT) was the elapsed time from the barricade launch or auditory alarm sounding to drivers initially lifting their foot from the accelerator. Movement time (MT) was defined as the elapsed time from drivers' first movement from the accelerometer to their initial application of the brake pedal. Stopping time (ST) was the elapsed time from the barricade launch or auditory alarm to the vehicle coming to a complete stop. Average deceleration (d) was the vehicle's average acceleration measured across the braking manoeuvre. Time to maximum pedal displacement (tmax) was the elapsed time from the initial brake pedal depression to the maximum pedal displacement. Maximum brake pedal force (Fmax) was the maximum force in pounds exerted by the driver's foot on the brake pedal over the course of the braking manoeuvre. Driver strength was the maximum force drivers could exert on the brake pedal, measured in pounds, while the vehicle was stationary.
In the experimental study, results show great differences between real driving and driving at simulator concerning pedal applied forces (e.g. 36 lbs and 196 lbs force in braking in real context and at simulator, respectively).

Variable	*M*	*Mdn*	*SEM*	*n*	*Min*	*Max*
Distance (m)	34.9	33.8	1.5	10	28.4	41.4
PT (s)	0.73	0.75	0.12	10	0.15	1.55
MT (s)	0.33	0.25	0.07	10	0.15	0.85
ST (s)	5.14	4.85	0.24	10	4.40	6.45
$\overline{d}$ (g)	0.48	0.50	0.03	10	0.35	0.61
t_{max} (s)	1.82	1.85	0.18	10	0.60	2.60
F_{max} (lbs)	36	42	5	10	11	57
Strength (lbs)	196	197	28	10	51	319

Table 11: Drivers' braking performance at the surprise condition (Fitch et al., 2010a)

Variable	M	Mdn	SEM	n	Min	Max
Distance (m)	32.9	32.6	0.7	53	22.2	53.1
PT (s)	0.56	0.55	0.02	53	0.15	0.95
MT (s)	0.22	0.25	0.01	53	0.10	0.45
ST (s)	5.56	5.20	0.19	53	3.65	9.35
$\overline{d}$ (g)	0.44	0.44	0.02	53	0.18	0.66
t_{max} (s)	1.32	1.10	0.10	54	0.35	3.05
F_{max} (lbs)	27	26	2	54	7	78
Strength (lbs)	201	172	13	52	51	476

Table 12: Drivers' braking performance at the expected condition (Fitch et al., 2010a)

Variable	M	Mdn	SEM	n	Min	Max
Distance (m)	22.2	22.6	0.1	177	19.3	33.7
PT (s)	0.30	0.30	0.01	142	0.10	0.85
MT (s)	0.25	0.27	0.01	125	0.15	0.90
ST (s)	3.55	3.65	0.04	177	2.65	5.95
$\overline{d}$ (g)	0.63	0.62	0.01	169	0.33	0.83
t_{max} (s)	0.85	1.00	0.05	172	0.20	3.00
F_{max} (lbs)	81	98	5	174	11	339
Strength (lbs)	201	172	12	60	51	476

Table 13: Drivers' braking performance to an expected auditory alarm (Fitch et al., 2010a)

Older drivers had a shorter mean stopping distance than younger drivers when braking to the expected barricade, which may be evidence of their driving experience. On the other hand, younger drivers had a shorter mean stopping distance than older drivers when braking to the expected auditory alarm, which may be a sign of their physical strength. Younger drivers pressed the brakes harder and had shorter times to maximum brake pedal depression than older drivers when braking to the expected auditory alarm. Male drivers had faster PTs, applied greater force to the brake pedal, and produced greater decelerations than female drivers when braking to the expected auditory alarm. These findings help explain male drivers' shorter mean stopping distance, as compared to female drivers, when braking to the expected auditory alarm and the expected barricade. The current study found that drivers' mean BRT to an expected auditory alarm was 0.55 s. To compare, Johansson, Rumar (1971) found drivers' median BRT to an expected "klaxon" sounded outside of the vehicle to be 0.66 s. Since drivers' median BRTs can be expected to be 0.2 s faster than mean BRTs (Green, 2000), this BRT discrepancy may be a result of Johansson and Rumar using an experimenter to mark the onset of vehicle brake lights, and then subtracting the experimenters' mean response time from the measured total response time to get drivers' BRT. Furthermore, since it is known that the auditory alarm loudness affects response time (Haas, Edworthy, 1996), it is also possible that faster BRTs were observed in the current study because the auditory alarm was more detectable than the klaxon used by Johansson, Rumar owing to the quiet interior of the newer vehicles. Nevertheless, the findings from the current study support Green's summary that drivers' BRTs to an auditory alarm are lower than their BRTs to a visual cue. Another research study performed by Hara et al. in 1998 focused on panic braking and reaction times. It highlights different efforts and applied forces related to situations and users' driving experience.

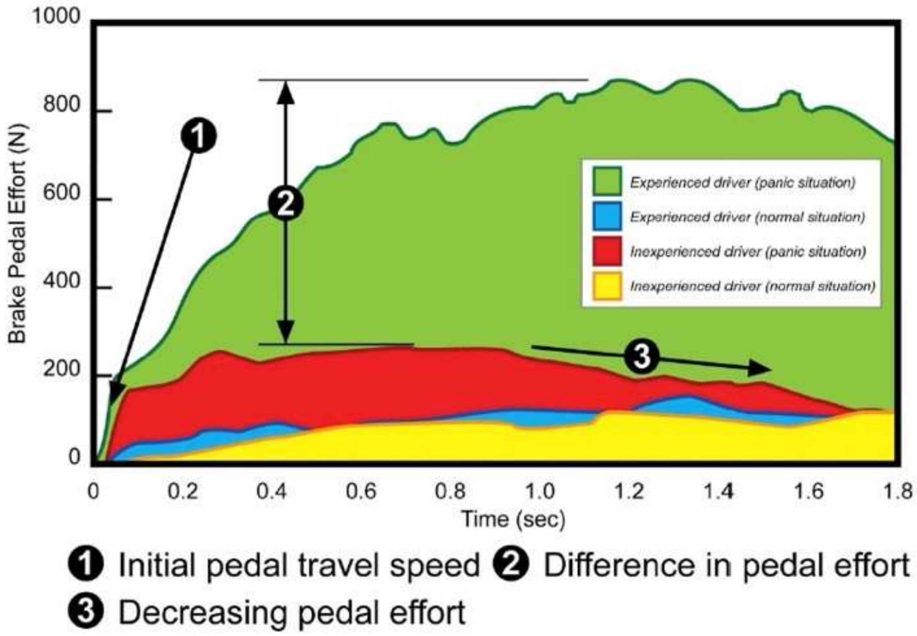


Figure 77: Pedal effort plotted against time during panic and normal braking (Fitch et al., 2010b)

Three main findings came from this research as listed below.

- There was a significant difference in the initial brake pedal application rate between normal and panic-braking situations. Additionally, the initial brake pedal application rate (within the first 0.05 s of the stop) was the same for the experienced driver who could generate sufficient braking effort and the inexperienced driver who could not.
- The initial pedal effort generated by the inexperienced driver was less than what the experienced driver generated. In fact, the maximum pedal effort realized by the inexperienced driver was less than one-third of that generated by the experienced driver.
- The braking effort generated by the inexperienced driver decreased throughout the braking manoeuvre (after 0.6 s).

Findings are representative of drivers of various ages and genders. Consequently, the research suggests that panic braking can be identified from the initial brake pedal application rate. Further testing showed that brake pedal displacement (i.e. the distance the brake pedal travels, also referred to as stroke in the literature) must also be considered because, in highway driving, a rapid initial brake pedal application rate frequently occurs in not panic braking scenarios. Fortunately, these not panic braking manoeuvres are distinguishable from panic stops by their shorter pedal displacements (Fitch, 2010b).

12.1.1. Relevant research studies about braking forces and deceleration

Some data and values about applied braking forces are reported below as example from detailed experimental studies.
For instance, a research activity involving bus drivers (GRSG-91, 2006) reported the following suggested forces for braking according to four levels of progressive actuation.

Braking	Force	Angle of operation	Type of operation
First response	**40 N ± 10 N**	**4° ± 1°**	**Ankle-operated**
20%	**120 N ± 30 N**	**8° ± 2°**	**Ankle-operated**
50%	**180 N ± 50 N**	**13° ± 3°**	**Ankle-operated**
100%	**≤ 420 N**	**≤ 25°**	**Leg-operated**

Table 14: Example Of Applied Braking Force In Coaches At Gradual Levels (Grsg-91, 2006)

Relevant investigations about braking actions and force requirements were performed by USA Department of Transportation since '70s (DoT, 1970). Past studies need certainly to be regarded with respect to technological context of reporting time. Technological development constantly in progress in automotive and braking industries could have changed users' perception and implied forces, but these studies could offer anyway an overview about the carried out research studies and point-out the measures as references.
In particular, researches showed the highest deceleration/pedal force gain resulted in sub-optimal mean deceleration on all pavement surfaces used in the test, resulted in high frequency of wheel lockup, wheel lockup duration, loss of steering control, and was down-graded in the subjective ratings. High gain and intermediate gain configurations provided best performance in terms of mean deceleration on the dry and wet surfaces, while lower gains were required on the wet-painted surface. This is what would have been expected, but the data also showed those deceleration/pedal force gains that could be used as boundary conditions, such that the gain levels should not be greater than nor less than indicated values. The limiting points and recommendations have been shown in next figures.

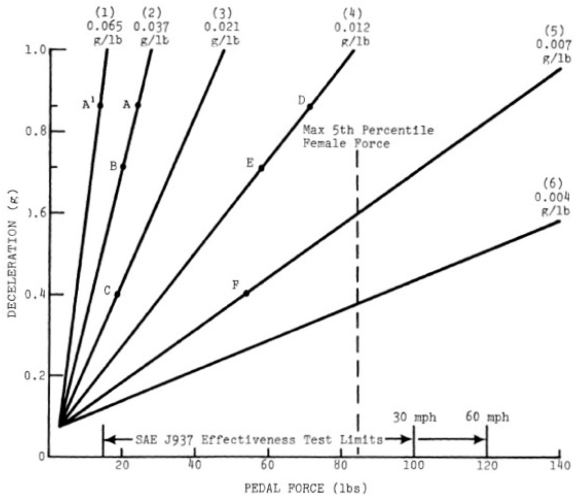


Figure 78: Cut-Off Pfg Values For Satisfactory Driver-Vehicle Braking Performance (DOT, 1970)

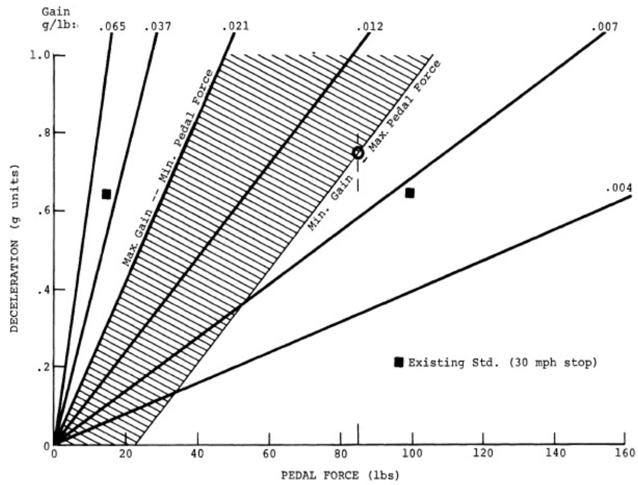


Figure 79: Recommended Deceleration/Pedal Force Space (DOT, 1970)

The most relevant outcomes from this study about braking forces are listed below (DoT, 1970).

1. The limiting maximum deceleration/pedal-force gain should be 0,21 g/lbs because:
   - C is the most critical limit and falls on this function;
   - higher pedal force gains incurred greater frequencies of loss of control and wheel lockup, wheel lockup duration and were downgraded in subjective ratings of force requirement;
   - practical restrictions on brake performance currently preclude a deceleration/pedal force curve in which the gain increases with pedal force. Therefore, a line of slope 0,021 g/lbs as the maximum gain and the bound on minimum pedal force in the deceleration/pedal force space.
2. The low gain limit in the deceleration/pedal force space is obtained as follows:
   a. the minimum gain a t which effective braking performance was obtained on all surfaces that were used is 0,012 g/lbs.
   b. the female 5th percentile foot force (85 lbs) should be sufficient to attain a deceleration of 0,75 g.

About emergency situation and warning, relevant researches focused on the relation of the situation variables, the context and the applied braking rate.
According with the assumption that when required braking rate reaches a threshold that represents the predicted driver emergency response, the driver should be warned. The specified braking rate represents the threshold that differentiates between non-alerts and alert situations.
For the purposes of an Advance Driving Assistance System as Forward Collision Warning, braking rate will be defined as the average deceleration that occurs between the moments when the driver first depresses the brake pedal and when closure rate is reduced to zero. It is important to differentiate braking rate from the maximum or peak deceleration rate, which is larger, because of

the time required to increase the deceleration rate from near zero to the maximum rate (SAVE-It, 2004).
Starting from the hypothesis than deceleration for an emergency-braking situation could be range between -0.4g and -0.85g and assuming braking rate as the average rate over the period of time starting with the initial brake depression, experimental studies defined -0,85g and -0,75g as excessively large values if the goal of the potential algorithm is collision avoidance. -0,75g was defined as an acceptable value if the goal of the algorithm is reduction of collision energy (SAVE-It, 2004).
A study performed by Greibe aiming at review standards of braking distances and highlight design recommendation involved 22 drivers, including professional and not professional drivers, testing braking actions in several road conditions driving and instrumented touring car.
Outcomes from that study reported an average pressure on the brake pedal for the whole of the braking run as 34,8 kg for the non-professional test drivers and 74,0 kg for the professionals ones.
And on average, T-Pedal > 10kg (T-Pedal defined as the time it takes from the pedal being touched until the pressure reaches at least 10 kg), was recorded as 0,83 seconds for the non-professional test drivers and 0,05 seconds for the professionals.
Not surprisingly, the non-professional test driver are slower to press the pedal “hard”, and overall, pressed the brake only approximately half as firmly as the professionals. However, there is large variation from one test driver to the next.
On wet road and at high speeds, the values are highest. This may be interpreted as being situations in which the test drivers brake most tentatively (Greibe, 2007).

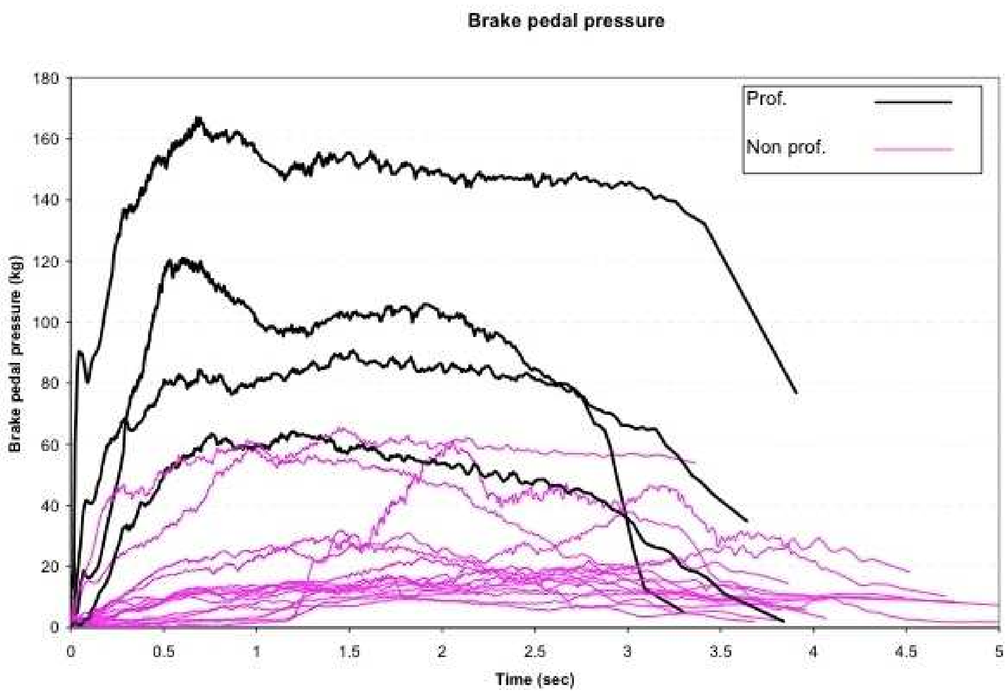


Figure 80: Braking Pedal Pressure During Braking By Professional And Non (Greibe, 2007)

12.2. Emergency Reaction and actuation times

In some "natural" braking actions, a fast accelerator pedal release, close to emergency situation actions, is relatively frequent on the road. A few of these actions are effectively linked to potentially dangerous situations. Taking into account other parameters, such as car's speed, distance to precedent car or drivers driving style, may increase the emergency braking recognition (Kassaagi et al., 2003).

Objective of study	**Results**	**Source**
Stretched reaction time in emergency braking situation	Mean 0,9s - Standard Deviation 0,3-2,0s	Johansson , Rumar, 1971
	All times < 2,5s	Koppa et al., 1997
	Mean 0,7s	ATZ, 1983
Factor influencing stretched reaction time	No influence from gender, weather or traffic conditions	ATZ, 1983
	Stretched reaction times prolonged by 0,4s if driver is not concentrating on the road	ATZ, 1983
	Stretched reaction time cut by approximately 0,4s if braking actions of the vehicle in front is accompanied by switched-on light	Libermann et al., 1995
	Not clear influence from the age, but young drivers do attain shorter stretched reaction times in the considered study.	Lerner et al., 1995
	Older drivers need longer stretched reaction times than younger ones.	Wierwill, 1990 Born , Chiang, 1996
	Significantly longer reaction times if driver is not concentrating on the road when stimulus occurs	Summala et al., 1998
	Purpose of journey, mental strain, nervous disease and drug consumption influence stretched reaction times	Summala, 2000

Table 15: Summary Of Published Data On Human Reaction Times (Source: Breuer , Bill, 2008)

Other studies showed that the drivers in emergency situations were far from using the maximal capacities of their vehicle, particularly in braking. For example, during an emergency braking experimental research study performed on track, 52% of the drivers have not reached the ABS regulation. In 57% of the cases, the hit on brake pedal contains a fall of brake pedal speed, with possibly a bearing in travel. For these reasons, it seems that if an Emergency Brake Assistance (EBA) was activated in all these cases, it would allow to improve in a significant way the performance of the braking (Kassaagi et al., 2003). The principle of such a system is to detect braking corresponding to critical situations and to amplify the assistance ratio of the braking system to help the driver to obtain earlier the maximal deceleration of the vehicle. The quoted study also highlights big differences between drivers' behaviour, which could be classified in "sports" and "slower". The drivers who have a "sports" behaviour are characterized by:

- higher speeds, close or over the speed limits on all infrastructures;
- higher transversal accelerations on any infrastructures except on highways;
- higher accelerations and decelerations in urban areas and on sinuous roads.

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