# EXPLOITABLE CHARACTERISTICS OF DRIVER BRAKING

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## ABSTRACT

Previous work (Perron et al., 2001) on emergency brake application concluded that driver population diversity and "the overlap of braking parameter distributions between normal conditions and emergency situations" is such, that triggering criteria cannot both detect all emergency braking actions and never activate the assistance in situations where it is not necessary. The objective of this study was to investigate driver-braking characteristics, in order that future systems might achieve greater effectiveness.

48 drivers drove an instrumented vehicle on a public road section before arriving at a test track, where they were instructed to follow at their preferred distance another vehicle towing a trailer. They were told the aim was to measure their preferred car-following distance. They were naïve to the fact that 0.2 miles down the track the trailer would be released and rapidly decelerate to a stop. The main variables analysed included "throttle-off" rate, brake pedal pressure/force, and clutch pedal pressure/operation.

The results indicate a series of relationships exploitable by an intelligent brake assist system. An intelligent brake assist system could take advantage of those characteristics and adapt its performance to individuals' braking style.

Limitations of the study include resource constraints (use of a single instrumented vehicle, time-limited access to the test track)and the contrived nature of the emergency braking scenario (need for surprise element, practically a one-off study, limitation of speed to 30mph/48kmph).

The study provides evidence of a background for a customisable brake assist system that learns from the driver and adjusts its full-brake trigger accordingly.

## INTRODUCTION

The huge potential of active safety systems can only be realised if driver input in the system is taken into account. Systems such as emergency brake assist, stability control and collision avoidance must be reliably triggered when drivers actually need assistance, but should not intervene in normal conditions. False alarms/interventions could have detrimental effects on driver acceptance of the system.

One problem with research on specific active safety systems is that because of its commercially sensitive nature, it often remains confidential to a large extent. Detailed research on ergonomic aspects of active safety systems often remains in the private domain and rarely is published. In one of the few exceptions, researchers working in the Laboratoire d' Accidentologique, Biomécanique et étude de facteur humain (LAB) published results of driver studies for the specification of active safety systems, and brake assist in particular (Perron, Kassaagi, & Brissart, 2001). Perron et al (2001) were the first to publish results of microscopic studies on driver braking in emergency conditions. They utilised both a driving simulator and an instrumented vehicle on a test truck to achieve their goal. In the simulator, four longitudinal accident configurations were examined: a vehicle coming out of a parking area into the subject's path, a vehicle stopped after a crest on a roadway, a vehicle moving at reduced speed after a crest, and a vehicle decelerating before braking strongly after being followed for 500m in an urban area. In the test track study, participants had to follow a vehicle with a trailer which was eventually released from a relative distance of 17m at a speed of 70km/h. Results indicated that while everybody braked, only 50% braked hard enough to activate ABS and only 80% of these exploited ABS function by swerving to avoid the obstacle. Authors concluded that if emergency brake assist was fitted to the vehicles, up to 40% of collisions would have been avoided and in another 30% of cases the impact speed would have been reduced by more than 15km/h. More than 70% of crashes would have been avoided if the brakes were activated at the throttle-off instant (approx 0.3 s in advance of actual braking). However, all these figures rely on "the hypothesis that the assistance is actually always triggered in emergency situations, which is an ideal case. Actually, due to the significant overlap of braking parameters distributions between normal conditions and emergency situations, triggering criteria based on a single braking parameter cannot both detect all emergency braking actions and never activate the assistance in situations in which it is not absolutely necessary"...

In an attempt to overcome this problem, researchers in LAB employed hybrid neural networks + genetic algorithm methodology in order to find parameters that could be used in combination to distinguish emergency situations from normal braking (Bouslimi, Kassaagi, Lourdeaux, & Fuchs, 2005). The result was a model that was quite successful in its purpose, however it relied on some parameters that were related to post-incident events – such as the result of the emergency manoeuvre, a fact that rendered it inapplicable in an intelligent brake assist system. Contemporarily, Schmitt and Färber (Schmitt & Färber, 2005) used Fuzzy-Logic to create a model that could distinguish successfully between normal and emergency braking. The model is based on three parameters of throttle-pedal operation: change of radius, jerk, and foot displacement time (from throttle to brake pedal). Data for this study was collected through the CAN bus of the vehicle 54 participants drove in a test-track study. Speed was restricted to 60km/h and the obstacle appeared en-route about 35m ahead of the vehicle. The authors claimed that their model predicts correctly 85% of emergency braking and 97% of braking before a corner, against 77% emergency braking and 99% braking before a bend correctly predicted by a system with a fixed trigger-level.

Recently, McCall and Trivedi (McCall & Trivedi, 2007) utilised Bayesian networks to fuse driver behavioural information with vehicle/environment information to predict an emergency or non-emergency situation. Inputs to the system include time-headway (from a LIDAR sensor), wheel speed, brake pressure, accelerator position, steering angle, vehicle longitudinal and lateral acceleration, yaw rate, steering angle and gaze and face expressions recorded using video-cameras. The authors provided supportive data of the effectiveness of the system in predicting critical situations; however they admitted that a significant problem was the number of false positives (undesired system activations). This was the case particularly when drivers covered the brake pedal but eventually decided not to brake. Although titled "brake support" by its authors the model aims more towards "brake automation" - automatic braking rather than augmented braking. It looks more towards vehicle-automation than towards driver-support.

A number of years has passed since the original introduction of (Emergency) Brake Assist systems in road vehicles and there is no published evidence that the challenge of accommodating the individual differences in driver braking has been achieved. The present paper provides an alternative approach towards the fulfilment of this goal. To achieve this, a human-centred approach is adopted. Individual differences are now seen as an exploitable opportunity rather than an obstacle towards successful human-machine interaction. The present study examines the relationships among basic parameters of driver longitudinal control and suggests how they could be exploited in an intelligent brake system to accommodate driver variability.

## METHOD

To achieve the aims of the study, 48 participants drove an instrumented vehicle on public roads and on a closed test-track. Each session allowed a combination of normal braking responses and an emergency braking episode to be recorded for each participant. The details of the study are presented below.

### Apparatus

A Ford Fiesta (2000 model year) was fitted with a camera in the footwell to record foot/pedal movements, an on-board camera provided view of the road ahead, two Tekscan Flexiforce® sensors were fixed on the brake pedal surface, one Flexiforce® on the clutch pedal surface, and a potentiometer was attached to the centre of the throttle-axis rotation. Sensors were calibrated according to Tekscan's guidelines (Tekscan, 2008). A Labjack® U12 data acquisition module was connected to a Toshiba® Tecra 3 laptop using Azeotech® DAQFactory® Express software for data logging. Power was provided through the vehicle's battery when the engine was on and through the laptop's battery when it was off.

**Figure 1: View from the on-board camera during the closed-track study**

**Figure 2: The trailer during built-up**

A lightweight (m<30kg) trailer was built for the purpose of simulating a lead vehicle's sudden braking ($a<-5m/s^2$) on the test track. The trailer's stopping properties were representative of average emergency decelerations of real vehicles in experimental (Vangi & Virga, 2007) and field studies (van der Horst, 1990). The trailer (figure 2) was three-wheeled for extra straight line stability; dimensions were 2.2m length, 1.25m rear width, 0.3m front width, and 0.4m height at the back. Wheels were 20inch standard road bicycle wheels. The structure comprised a sheet of waterproof wood reinforced with an aluminium skeleton. Two 0.75mx0.5mx0.5m cardboard boxes were filled with closed empty plastic bottles and wrapped with white plastic bags before they were attached at the rear of the trailer to create a "bulkiness" illusion (figure 1). Standard bicycle "V-brakes" were installed and were activated by the rotation of a lever which was activated by two springs upon release from the car. During testing average acceleration of the trailer after release was -6.81m/s$^2$ with an instantaneous minimum of -17.24m/s$^2$ achieved.

**The participants**

Participants were recruited through advertising in local press and local companies. Forty-eight drivers (26 male and 22 female) participated in the study. Age ranged from 21 to 84 (average 31.3) years, average driving experience was 12 years (min 1, max 48), and the average mileage was 9653 miles/year (min 2000, max 30000). They all held a full driving license (UK/EU or equivalent international) and had 3 or fewer penalty points.

**The route**

The public road section of the route driven by the participants included an urban and a rural section (11km in total) that led them from the start (Loughborough University Business Park) to the test track (Wymeswold Airfield). A section of the track was isolated and marked out with cones to provide a single lane for the emergency brake test. Sessions took place between 5 and 8pm on weekdays in daylight (Spring-Summer).

**The test protocol**

Participants provided personal details for insurance purposes before the experiment, as well as demographic data and a general health questionnaire. Just before the start of the driving session, they indicated their stress level on a 7-point Likert scale. They were told that the purpose of the study was to measure their preferred driving distance from other vehicles and for that purpose they would have to follow an instrumented trailer that would record this distance on the test track. Upon arrival to the test track they would stop at the entrance before an experimenter would check the site and give permission to proceed to the track. There, they were asked to follow another vehicle towing a trailer around the track at their preferred distance. They were told that this was the target variable of the experiment. Post-trial questioning confirmed that they were naïve to the fact that the trailer would be released after 0.2 miles (321.86 m). In each trial the lead vehicle accelerated to 30mph (speed measured using GPS) and kept a constant speed until the release of the trailer.

**Data analysis**

Participants' stress index before the study was compared to their stress rating immediately after the test-track study. Because of the non-parametric nature of the data, a Wilcoxon test was used. In order to examine the appropriateness of using brake force and/or "throttle-off" rate as single triggering criteria, mean values for the public road section were compared to the peak values during the emergency response. Paired Student's T-test and Wilcoxon test was employed for that purpose. Then, in order to examine the relationship between normal and emergency braking, each variable in the public road driving condition was plotted against the same variable in the emergency braking condition. Various regression models were tested in order to find the model with the best fit to the observed data. All the analyses were carried out using the Statistics Package for Social Sciences (SPSS) ver. 15.

## RESULTS

**Table 1.**
**Wilcoxon signed ranks test results for stress before and after test-track study**

| Stress after – stress before | Negative ranks | Positive ranks | Ties | Total |
|---|---|---|---|---|
| N | 3(a) | 33(b) | 11(c) | 47 |
| Mean Rank | 20.00 | 18.36 | | |
| Sum of Ranks | 60.00 | 606.00 | | |
| Z | -4.384(d) | | | |
| Asymp. Sig. (2-tailed) | .000 | | | |

a stress_after < stress_before
b stress_after > stress_before
c stress_after = stress_before
d Based on negative ranks.

Analysis of the drivers' self-rated stress-level before and after the emergency event on the test track indicated an increase in participants' stress-level (table 1). The resulted difference is statistically significant at $p<0.0001$ level.

Quantitative analysis of brake response indicated that about 50% of participants did not use the brake significantly, either because they swerved enough to avoid the obstacle, and/or they were following with long enough time-headway to gear-down and stop gradually. These data had to be cleaned because participants did not engage brakes to stop the vehicle. Figure 3 presents the resultant distribution of brake-force response of participants that used brakes (force on sensor>5N). To further improve the normality, three more outliers on the upper end of the distribution were removed from further analysis. Then, the relationship between the peak force during emergency and the typical force during normal driving (public roads) was explored.

**Table 2.**
**Paired T-test comparison of force between normal and emergency braking (in Newtons, measured on each sensor)**

| | Force on sensors, public road driving – Force on sensors, emergency event |
|---|---|
| Mean difference | -14.24443 |
| Std. Deviation | 11.50758 |
| t | -6.189 |
| df | 24 |
| Sig. | .000 |

Table 2 displays the results of a paired comparison between each participant's typical normal and peak emergency brake force. The difference is statistically significant at level $p<0.0001$. There seems to be a relatively constant difference between the two conditions **per individual.** Further, scatter-plot of typical normal braking against the respective emergency response (force) can be found in figure 4.

Linear and non-linear models were tested and the three best fitted ones are shown in figure 4 (linear, quadratic and cubic). Analysis of Variance (ANOVA) for each model indicated that the cubic model is yields the highest correlation value ($R=0.51$) but the worst statistic significance ($p=0.09$) of the three. The linear model explains less variance ($R=0.45$) but is more statistically significant ($p=0.02$). The quadratic model on the other hand is in between; Pearson R for this model is 0.50 and statistic significance is $p=0.03$.

Then, throttle-off characteristics for the whole dataset were examined. Figure 5 displays comparative values of throttle-off rate for each driver between normal and emergency conditions. In only 7 out of 58 cases are the respective values similar. A Wilcoxon test indicated a statistically significant difference between the two variables ($p<0.0001$).

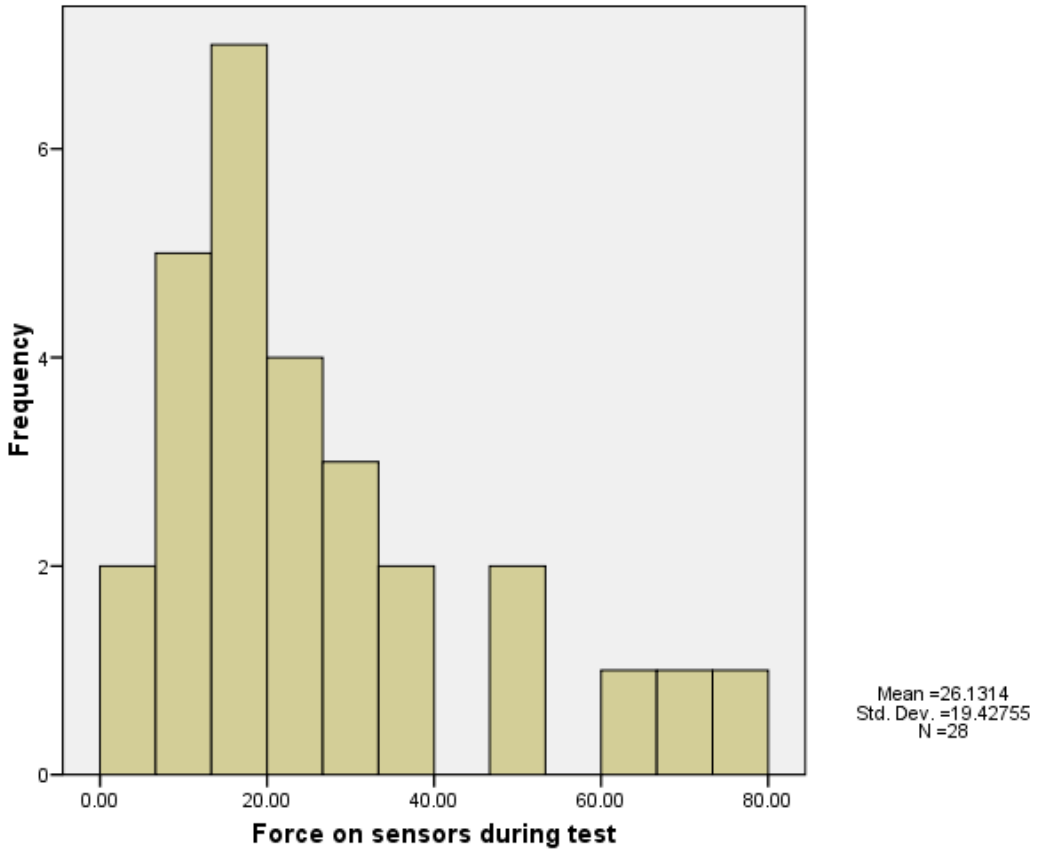


**Figure 3: Histogram of forces measured during emergency brake test after cleaning of data (force in Newtons, measured per sensor)**

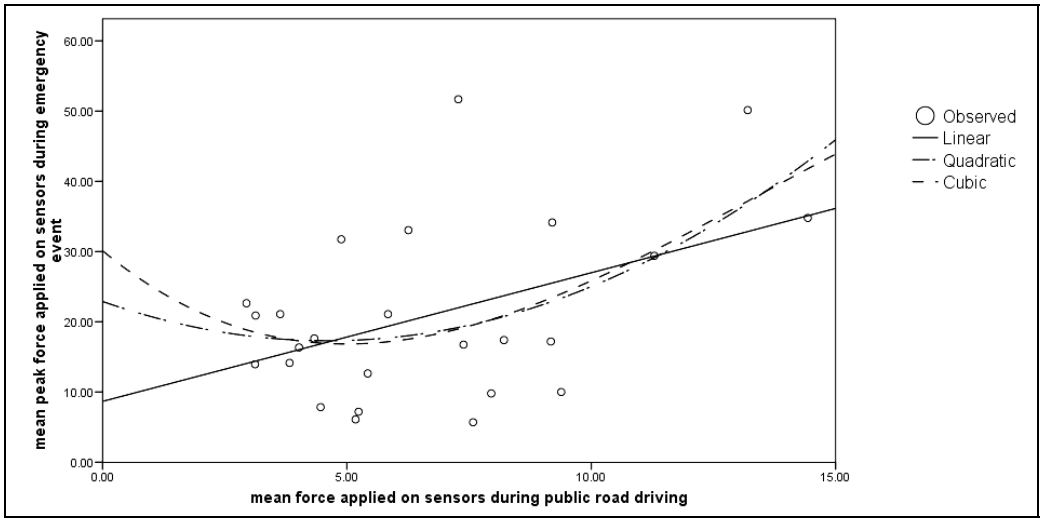


**Figure 4: Scatter-plot and best fit models of participants' normal and emergency braking in terms of force (measured in Newtons per sensor)**

## DISCUSSION

It is impressive how different the two conditions look through the paired-comparison for each participant. Both throttle-off and brake force distinguished very well ($p<0.0001$) between normal and emergency conditions per individual. However, as was the case in a previous study (Perron et al., 2001), this is not the case when drivers are mixed in a group. Some drivers' emergency response is quantitatively similar to somebody else's typical braking. There is a difference though between throttle-off and brake force.

Throttle-off distributions are much skewed (figure 5). Although the low resolution of the data acquisition equipment (8bit) plus the limited range of throttle-pedal movement in the vehicle's footwell could be partly blamed for this, the concentration of data in two groups is quite apparent. Thus, if a constant trigger-parameter is used, throttle-off has an advantage over brake-force. Actually if in our case the trigger was set to 0.6 degrees/sampling (figure 5) then it would have been correctly activated in 88% of cases and would have missed only 12%. Despite the reservation because of equipment limitations (data acquisition and vehicle properties), it should be mentioned that this is a much more effective intervention of a single/constant-trigger than the 77% quoted by Schmitt and Färber (2005).

The answer to the overlap between normal and emergency braking among drivers could be in relationships like the one portrayed in figure 4. This is because if there is a relationship that explains the variance between them in normal and emergency conditions, then the "normal" value could be used to predict the "emergency" value. For example the quadratic fit model on figure 4 could be used to predict the emergency brake value for participant X, if his/her typical (average) normal value is known (see example in next section). Now, when it comes to deciding which model to use for this purpose, each one of the three pictured in figure 4 has its merit. The linear model has more academic than practical value; it is conceptually best as a model representing the dataset ($p=0.02$), however it is worst in explaining the variance and predicting exact data points ($R=0.45$). The cubic model is best explaining variance and predicts most exact data points ($R=0.51$), however its representation of the whole dataset is problematic ($p=0.09$). The quadratic model is almost as good as the best aspect of both models ($R=0.50$, $p=0.03$) and seems to combine both merits. It remains though to be tested in practice.

Other points that need mentioning are the external validity of the study and the unusual presentation of quantitative results. The study was designed to represent real drivers in conditions that were as realistic as possible. Participants were recruited from the local population and were not restricted to university students, test drivers, customers of a specific brand or recruited through a "participants' list". Of course, the absence of active involvement by a manufacturer, made data acquisition a lot more laborious task than it would have been otherwise. As for the emergency test itself, allowing the drivers to follow at their preferred distances effectively sacrificed half the sample, however this sacrifice enhances validity as it replicates the "insignificant" braking found in 50% of rear-end collisions/longitudinal critical events (Gkikas, Richardson, & Hill, 2008; Perron et al., 2001). Furthermore, subjective stress ratings by the participants themselves (table 1) support the validity of the emergency test. Most importantly, **all** participants reported surprise. Objectively, the average deceleration of the trailer is below the maximum achievable by modern vehicles, however it is comparable to actual decelerations observed in the field (van der Horst, 1990) and measured in tests with real drivers (Vangi & Virga, 2007).

Most of the numerical values quoted here are hard to embed in any type of system as they are. We could have quoted the values in SI units or use force values for the whole brake pedal instead of just one area on it. However, the major findings are the relationships that emerge from the results and which can be exploited in a vehicle system to improve safety. In the next section an example is presented of how to exploit these.

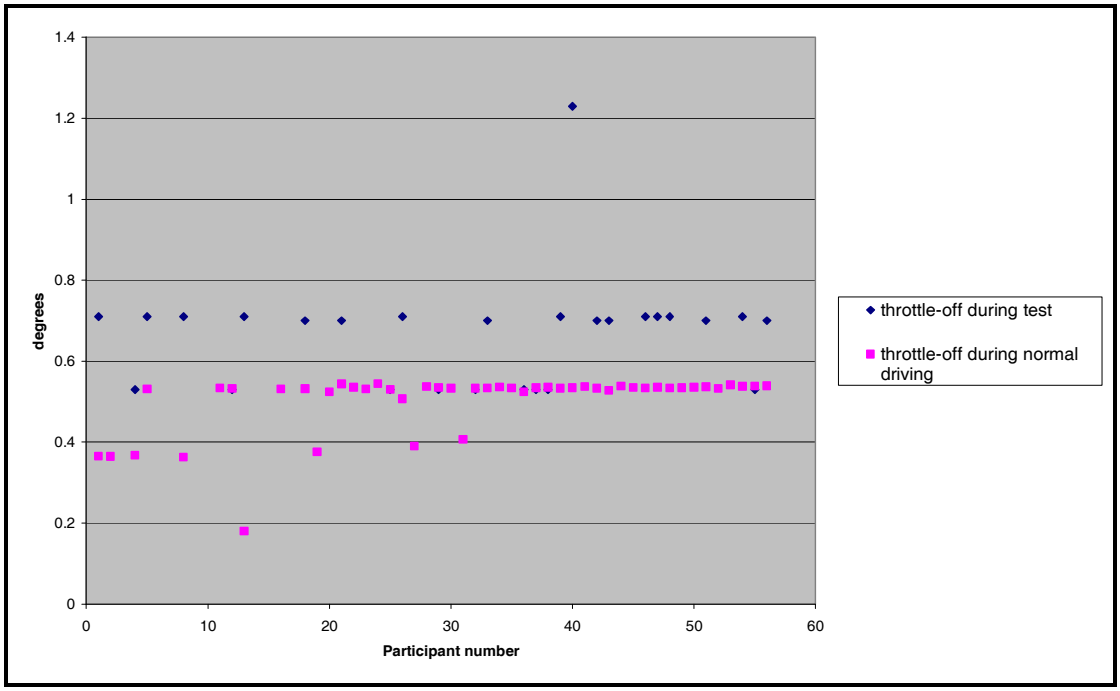


**Figure 5: Throttle-off rate in normal and emergency conditions (degree/sampling)**

## APPLICATION

In the last section of the paper, an example will be provided of how the relationship between normal and emergency braking can be exploited to accommodate driver variability. Figure 6 presents a system specification that could exploit this relationship, by incorporating the quadratic model to predict the appropriate trigger level for full-brake activation.

At the start of the drive the trigger is set to the average emergency brake level as measured in the study (Tr in figure 6). Then every time force is applied on the brake pedal, the system calculates based on the input a new trigger-level [Tr(1) in figure 6], which fuses the new [Tr(1)] with the previous (Tr) to give out the new trigger [Tr(n)]. If this value is exceeded during braking, then full-brakes are applied.

As an example, figure 7 is a simulation of how this system would work based on the drive of one participant. It is quite interesting that the system within a few seconds is below the participant's actual emergency brake force (last high-wave in the graph). In this simulation full brakes would have been engaged twice on the way to the test track. Cross-check with the video of the drive indicates that those two would happen at two urgent stops before traffic lights in yellow-phase. Of course, the system would be activated during the emergency test (far-right section of figure 7).

The above is one example of how the results from this study can be exploited by an adaptive brake assist system. Cubic or linear models can be used as well, or even different layouts of the agents in the system in figure 6. These remain to be tested on their relative merits in practical terms. It was not the purpose of this article to provide a ready solution to be implemented in brake assist systems; however it was an objective of this study to present the characteristics of driver braking that engineers can exploit when specifying the function of their systems. The authors are satisfied that this first step is achieved.

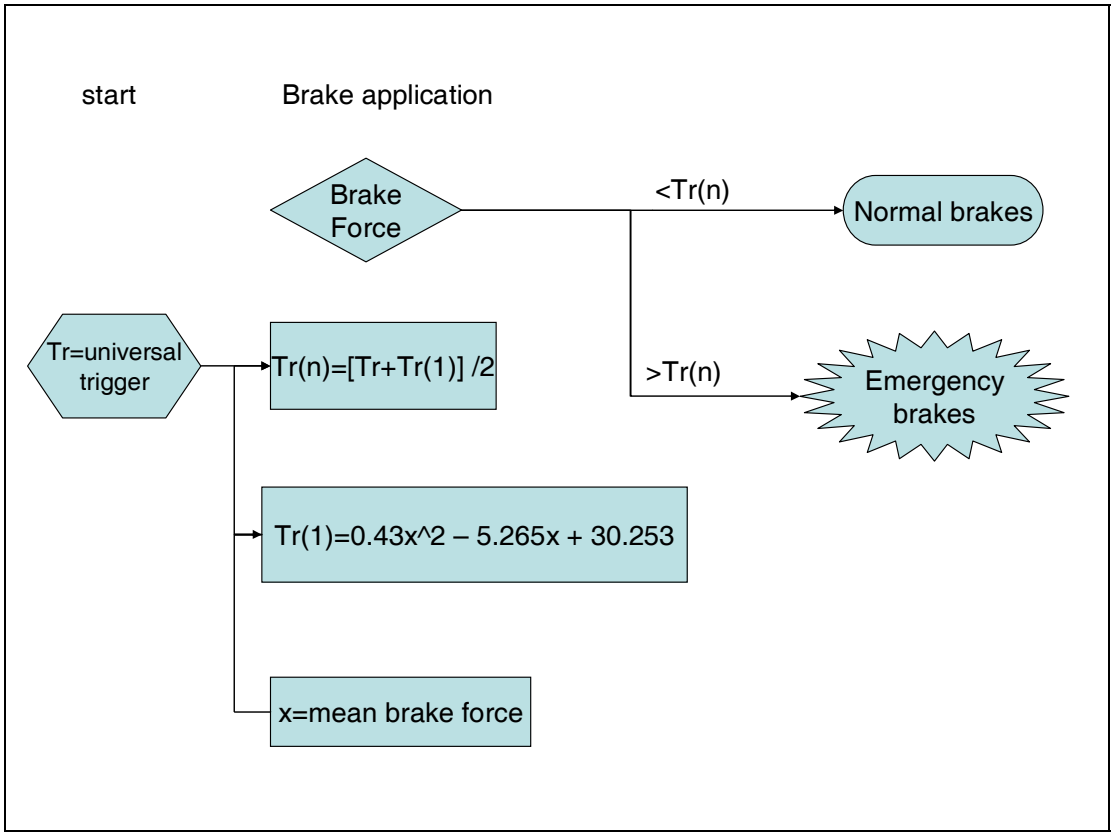


**Figure 6: Example adaptive function of the system**

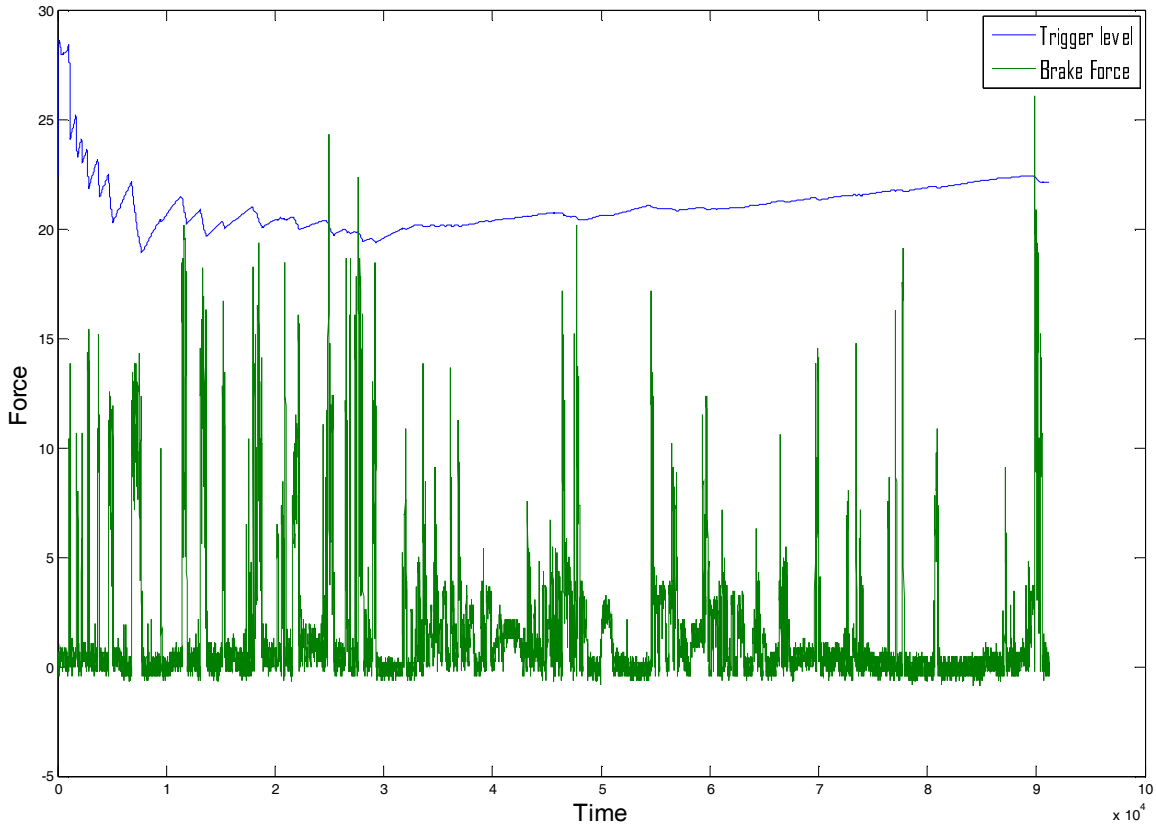


**Figure 7: The function of the system according to a participant's driving**

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