

# EFFECTIVENESS OF AUTONOMOUS BRAKING SYSTEMS

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SAMMANFATTNING

The objective of this study was to calculate the effectiveness of a pedestrian injury mitigation system that brakes autonomously prior to a crash. The effectiveness was primarily measured by the reduction of pedestrian fatality risk. The study was limited to accidents where the pedestrian was hidden during the seconds prior to crash and then got struck by the front end of the car. Data about real life accidents were collected at the database from the German In-Depth Accident Study (GIDAS). Through statistical analysis of the data, dependencies and distributions for the different variables were evaluated. These were then used to generate thousands of similar accidents. This enabled simulated tests of the autonomous braking system to evaluate its effectiveness. The simulation was made with MATLAB and was based on a system with a set of standard properties. It was also analyzed how variations in these properties affects the system's effectiveness. The study documents that an autonomous braking system with the chosen standard properties would reduce the average risk of fatality with 70 %. Improvements of the system's properties would only lead to marginal effects on the effectiveness.

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## Abstract

The objective of this study was to calculate the effectiveness of a pedestrian injury mitigation system that brakes autonomously prior to a crash. The effectiveness was primarily measured by the reduction of pedestrian fatality risk. The study was limited to accidents where the pedestrian was hidden during the seconds prior to crash and then got struck by the front end of the car. Data about real life accidents were collected at the database from the German In-Depth Accident Study (GIDAS). Through statistical analysis of the data, dependencies and distributions for the different variables were evaluated. These were then used to generate thousands of similar accidents. This enabled simulated tests of the autonomous braking system to evaluate its effectiveness. The simulation was made with MATLAB and was based on a system with a set of standard properties. It was also analyzed how variations in these properties affects the system's effectiveness. The study documents that an autonomous braking system with the chosen standard properties would reduce the average risk of fatality with 70 %. Improvements of the system's properties would only lead to marginal effects on the effectiveness.

## 1. Introduction

During the last few years focus in development of automotive safety systems have changed. The cars of today do not only mitigate the consequences of a crash, they are also supposed to prevent many of the accidents to even occur. Some of the most vulnerable participants in traffic are the pedestrians and therefore several systems for their protection have been developed recently. Some of these are autonomous braking systems that detects pedestrians and brakes the vehicle if an accident is about to happen.

The benefits of an autonomous braking system have so far been measured mostly from its potential mitigation of pedestrian injuries. These benefits are mainly due to the fact that even slight reductions in impact speed have large effect on the pedestrian injury severity. One aspect of the effectiveness of these systems is, however, less explored. This aspect concerns the question of to which extent accidents could be prevented or mitigated in real life situations. In this study we will use an accident database to analyze a specific type of event and from that evaluate the theoretical effectiveness that an autonomous braking system would have in these events. This will give an understanding of the possibilities and limitations of autonomous braking systems.

## 2. Objective

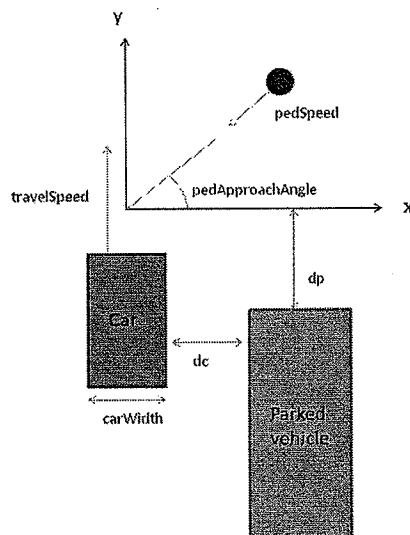
The goal of this study is to study the positive effects of an autonomous braking system to reduce the speed in pedestrian accident situations. To understand how pedestrian accidents occur statistical analysis of real life data will be done. By means of that analysis many statistically reliable accident scenarios will be generated to simulate typical events. The simulation, which will be done in MATLAB, will set up, simulate and visualize the event during the seconds prior to collision, with and without the autonomous braking system.

By means of the simulation and visualization it will be possible to evaluate the theoretical effectiveness that an autonomous braking would have in mitigation of real life accidents. The effectiveness will be assessed with the following questions in focus.

- Would an autonomous braking system with reasonable properties have a better chance to avoid accidents than drivers?

GIDAS-variables	Description	Unit	Collected/derived
dp	The distance in y-direction from the obstruction object to the collision point. See figure 1.	m	Derived
dc	The distance in x-direction from the obstruction object to the vehicle's nearest side. See figure 1.	m	Derived
travelSpeed	The speed at which the car was traveling before the event. See figure 1.	m/s	Collected
pedSpeed	The speed at which the pedestrian was walking at the event. See figure 1.	m/s	Collected
pedApproachAngle	The angle that the pedestrian was approaching with. The angles are the same as in the trigonometric unit circle. See figure 1.	deg	Collected
carWidth	The width of the car. See figure 1.	m	Collected
collisionSpeed	The speed at which the collision between the car and the pedestrian occurred.	m/s	Collected
driverBrakeDeceleration	The deceleration that the driver's braking gave.	m/s <sup>2</sup>	Collected
driverBrakeDistance	The distance from the collision point where the driver braked.	m	Collected
impactPoint	The distance from the mid of the car that the pedestrian was struck. Positive values means right side of the mid and vice versa.	m	Collected
timeOfDay	The light condition at the event. Daylight is considered as one condition and dusk/dawn/night is considered as one. Day is denoted by the number 1 and dusk/dawn/night is denoted by 2.	-	Collected
maxBrake	The maximum braking force that was possible due to the weather conditions and the surface type at the accident spot.	m/s <sup>2</sup>	Derived

**Table 1.** Description of GIDAS-variables



**Figure 1.** Illustration of GIDAS-variables. In the simulations the mid of the vehicles front is always in origo at the time of the collision.

### 4.2 Dependency of data

To evaluate the distributions of the data the dependence between the different variables was examined. The dependency was analyzed by setting up scatter plots. By means of these plots a dependency scheme was set up. Figure 3-5 are examples of the scatter plots that were used in the analysis. Figure 3 shows that the brake distance seems to be exponentially growing with growing travel speed. Figure 4 shows an example of two variables that seem to be independent of each other and figure 5 shows an example of linear dependency. This analysis resulted in a dependency scheme that is found in figure 6.

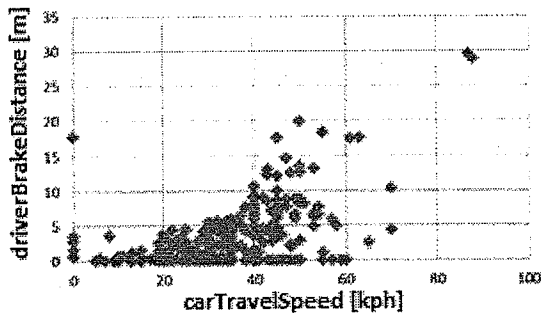


Figure 3. Scatterplot of driverBrakeDist as function of travelSpeed.

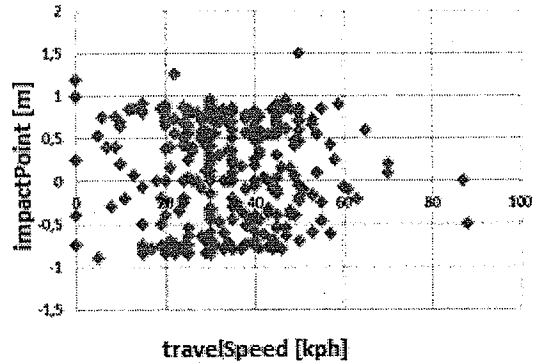


Figure 4. Scatterplot of impactPoint as function of travelSpeed.

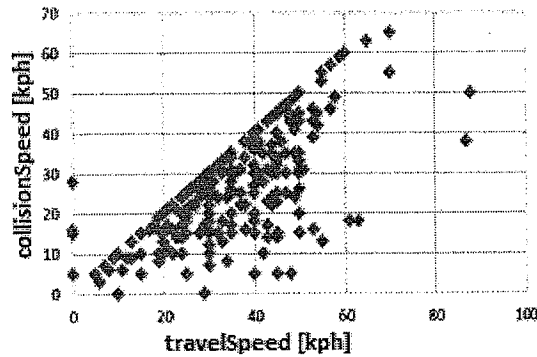


Figure 5. Scatterplot of collisionSpeed as function of travelSpeed.

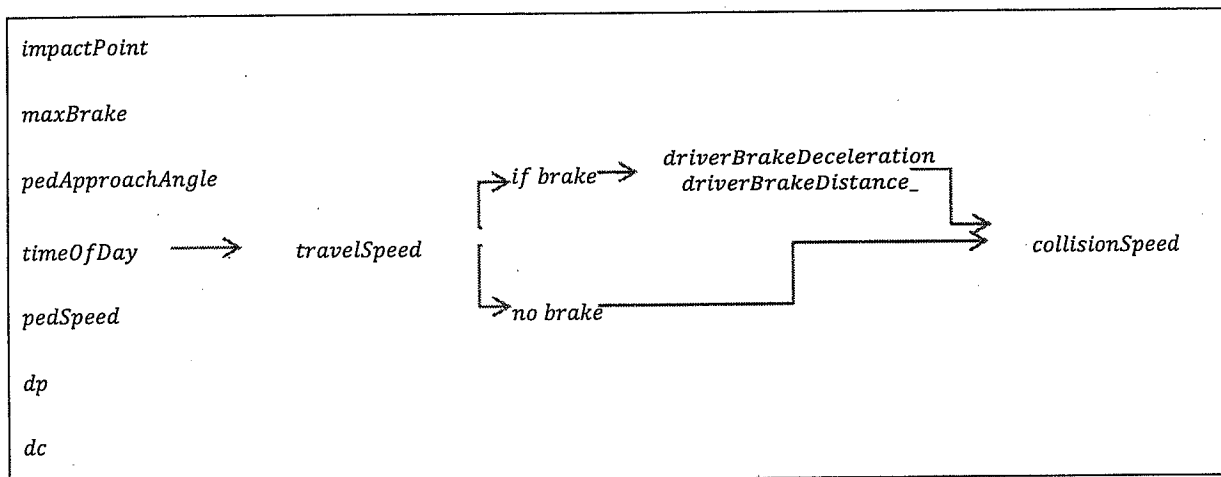
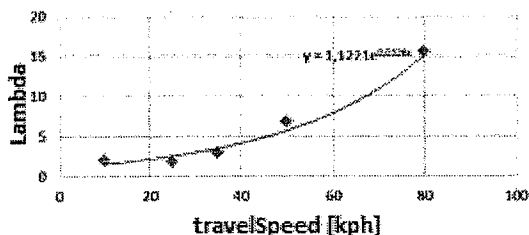


Figure 6. Illustration of dependencies between variables.

Every section was analyzed in SAS Enterprise Guide as an exponential distribution. From these five distributions for the different sections, five different rate parameters ( $\lambda$ ) were calculated. The evaluated rate parameters were used to set up a function with Excel. The estimated rate parameters are plotted against car travel speed in figure 9.



**Figure 9.** Mean values for each interval as function of travelSpeed. The line is a fitted trend line.

To set up a function for the rate parameters at different speeds a trend line was set up with Excel. This trend line gave the equation:

$$\lambda(v) = 1.1221e^{0.0326v}$$

Finally, the probability distribution for driver brake distance given the car travel speed became:

$$f(d | v) = \lambda(v)e^{-\lambda(v)d}$$

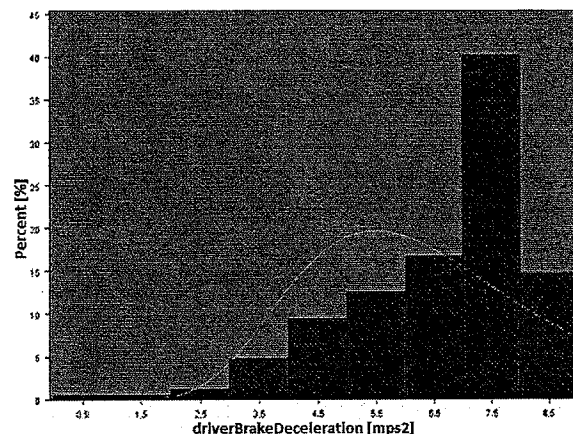
In the equations  $d$  is driverBrakeDist and  $v$  is travelSpeed in km/h. These equations were used to set up a distribution for driverBrakeDist for a given travelSpeed.

*Distribution of driverBrakeDeceleration and maxBrake*

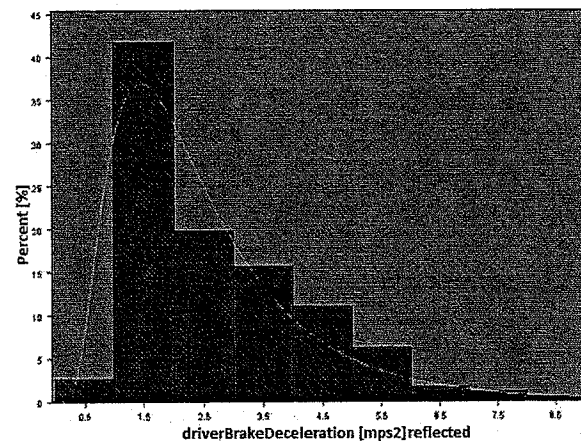
To evaluate a distribution for maxBrake, the limitation for maximum brake deceleration according to the surface of the street had to be considered. The maximum brake level for each surface with consideration to the weather

condition was set up according to the information in GIDAS database following Danner and Halm (1994) (Danner, M., Halm, J.).

The GIDAS data that describes driverBrakeDeceleration and maxBrake could not be fitted to any distribution with SAS Enterprise guide. The problem that prevented SAS for setting up distributions was that both datasets histogram were right weighted as shown in figure 10.



**Figure 10.** This figure shows the distribution for driverBrakeDeceleration.



**Figure 11.** This figure shows the distribution for the reflected driverBrakeDeceleration.

To be able to set up a distribution for this kind of dataset the dataset was mirrored to obtain a left weighted appearance. To establish that appearance the data set is subtracted by the

pedApproachAngle ( $\alpha$ ) and impactPoint ( $x_{pc}$ ) where the impact occurred:

$$x_p(T) = T * v_p * \cos \alpha + x_{pc}$$

$$y_p(T) = T * v_p * \sin \alpha$$

The positions of the car and the pedestrian were calculated for 2 seconds before the impact up to the time of the impact (in  $T = 0$ ). After the actual impact the time was considered to be negative ( $T < 0$ ). When plotting each time-step as a movie a figure like that in figure 12 appears.

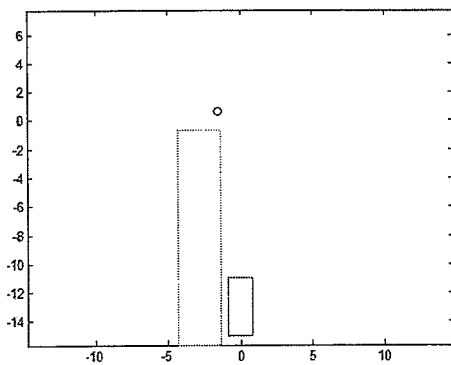


Figure 12. The pedestrian is shown as the circle, the blue box is the car and the green box is the obstruction object.

#### 4.5 Simulation

To simulate how an autonomous braking system would affect accident situations like these in this study the following assumptions about the system was made:

- The detection sensor is a camera with sample-frequency 25 Hz, the autonomous braking system will have the same frequency.
- The system needs five frames to make a certain detection of a pedestrian.
- The field of view of the sensor is 40 deg.
- The range of the sensor is unlimited. In practice this means that we assume that the sensor has a range of 100 meters.

- The system will brake with a maximum deceleration of 0.6 times the gravitational constant ( $9.81 \text{ m/s}^2$ ). The deceleration is also limited by the weather conditions and the road surface type.
- The system will brake if the driver has not already braked when the time to collision (TTC) is less than one second. The system will also brake if the driver brakes softer than the system brake level.
- The sensor is placed at the mid of the vehicle front end.

The standard values of the system parameters were chosen with respect to common limits of similar systems' components. For example the standard value for the field of view was based on the properties of Autoliv's present systems. The parameters are listed in table 3 below with the names that are used in the rest of this report.

Name	Description	Value	Unit
frameRate	The update frequency of the sensor, i.e. 25 Hz frame rate means that one frame lasts for 0.04 seconds.	25	Hz
sensorPosition	The distance from the vehicle front end to the sensor. sensorPosition = 0 means that the sensor is at the front end.	0	m
sensorRange	The maximum distance at which the sensor can detect pedestrians.	100	m

$$p_{fatal}(v_c) = \frac{1}{1 + e^{(6.9 - 0.09*v_c)}}$$

Where  $v_c$  is the impact speed in km/h. The collision speed ( $v_c$ ) reduction for each event was calculated as:

$$\Delta v_c = v_{c,without\ system} - v_{c,with\ system}$$

The proportion of the simulations where the system was activated was calculated as:

$$\frac{\text{number of times the system was activated}}{\text{number of accidents simulated}}$$

The proportion of the simulations where the accident was prevented was calculated as:

$$\frac{\text{number of times that the collision was prevented}}{\text{number of accidents simulated}}$$

A collision was considered as prevented either if the car managed to brake until it stood still, or if the pedestrian managed to get out of the way due to the autonomous braking.

#### 4.7 System properties

To analyze how variations in the system parameters would affect the effectiveness of the system the parameters were varied one at a time. As one parameter was varied the other were kept fixed at their standard values. The interval for each parameter was chosen due to physical and reasonable limitations as follows:

- *fieldOfView* was varied between 20 -180 degrees.
- *brakeAtTTC* was varied between 0.2-2 seconds before impact.
- *systemBrakeLevel* was varied between 0.4 -1 times the g force.
- *trackingTime* was varied between 1-10 numbers of frames before system activation.

- *frameRate* was varied between 10- 50 Hz.
- *sensorRange* was varied between 10-50 meters.
- *sensorPosition* was varied between 0-1.5 meter due to the length of the bonnet of a regular car.

## 5. Result

### 5.1 Distributions

To evaluate how well the distributions fitted to the original data from GIDAS that it was based on, a thousand data points were generated from the distribution and compared to the original data points. Their cumulative distributions were plotted in MATLAB. An example of the results of these plots is shown in figure 14. The red line represents the thousand data points that were generated and the blue line represents the original data from GIDAS. The two lines should be on top of each other for the distribution to be well fitted.

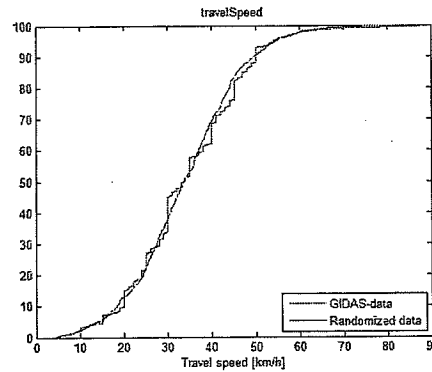
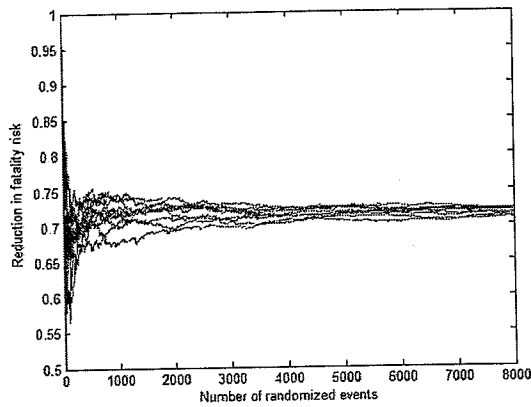


Figure 14. Cumulative distribution of travelSpeed.

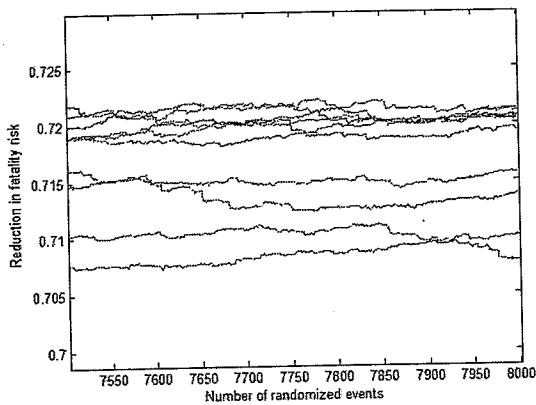
The distribution for driver brake distance did not generate optimal data points. The cumulative distribution for this variable is shown in figure 15. To obtain a better fitted distribution with the method that was used more data would have been required. The lack of data resulted in slightly too short generated distances from the distribution.





**Figure 19.** The average risk of fatality as function of number of simulations.

As one can see in figure 19 the mean value start to stabilize at about 1500 simulations. After that the curves converge successively. An enlargement of the right end of the plot is shown in figure 20.



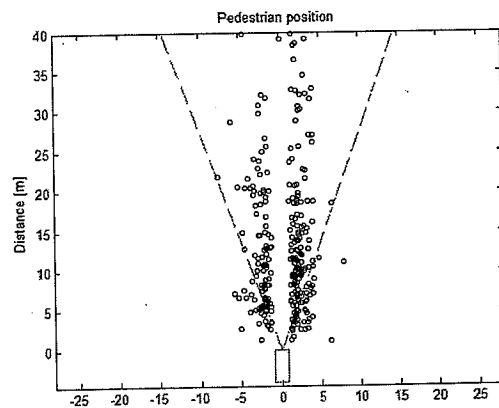
**Figure 20.** Enlargement of the right end of figure 19.

Figure 20 show that at 8000 simulations the results vary in an interval of 2 percent units. 8000 simulations were therefore assumed to provide enough reliability.

### 5.3 Potential effectiveness

In all of the accidents in this study the drivers said that the pedestrian was hidden before the impact. However, in many of the accidents the pedestrian would have been possible for an

autonomous braking system to detect relatively early and hence mitigate the effect of the impact. This is illustrated in figure 21, which show the position of the pedestrian relative to the car when first visible from the sensors position. The visibility in this case is independent of the sensors field of view and all other system parameters. It simply means that the pedestrian was no longer hidden by the obstructing object for a sensor placed at the vehicle front end.



**Figure 21.** The position of the pedestrian when first visible from the sensor's position. The dashed lines symbolize the field of view of the sensor.

Figure 21 show that a sensor with a field of view of 40 degrees or more would be able to detect many of the pedestrians at long distance. Figure 22 shows a histogram of the time to collision (TTC) when the pedestrian was first visible. Figure 23 shows the cumulative distribution for the same data. The TTC is calculated from the sensor's view and is based on the vehicles speed when the pedestrian became visible. The rightmost part in both figure 22 and 23 includes all events where TTC was greater than 5 seconds.

started to brake and the blue when the driver braked.

### 5.5 System properties

To evaluate how variations in the system parameters would affect the system's effectiveness one variable at the time was varied while the other variables were kept fixed. For each tested value of the system parameters 8000 accidents were simulated. An example of the result is found in figure 25. In the figures the four different effectiveness measures are plotted as a function of the sensor's field of view. All of these plots are found Appendix 2.

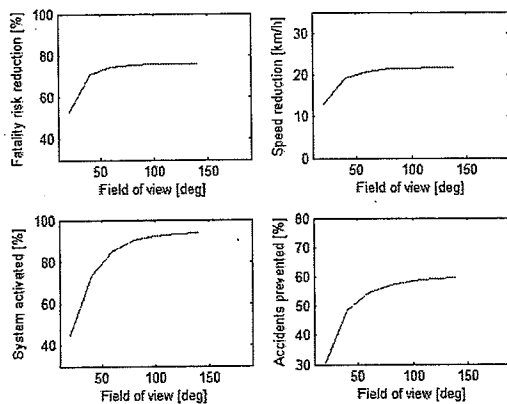


Figure 25. Effectiveness measures as function of field of view.

These tests may give an understanding of which properties of an autonomous braking system that would be worth to change or develop further.

The tests showed a slight potential increase of effectiveness with a better field of view in the sensor. A field of view of 120 degrees would reduce the average fatality risk with about 5 percent units added to the 70 % that was obtained with standard sensor. The tests also showed that if systemBrakeLevel was increased to 0.8g the risk of fatality would reduce with about 15 units of percent. The same increase

would have been obtained if trackingTime was reduced to only one frame. The rest of the tests showed that improvements of the other system properties only gave marginal effects on the effectiveness.

## 6. Discussion

The result of this study shows that an autonomous braking system of the specified kind, under the specific circumstances in the simulations, would reduce the fatality risk by an average of 70%. In darkness the average is as high as 74%. This result is all due to that the drivers in this study tend to drive faster in darkness than in daylight. The result might be considered as a bit uncertain since little is known about the sensor. The sensor might well show desirable functional variations depending on the light conditions. These variations have not been taken into the analysis in this study. In that sense the results from daytime simulations might be more reliable.

Real life autonomous braking system show several physical limitations that are not simulated in this study. One of the most important of those is the so called ramp up time of the braking system. The ramp up time is the time passed from when the brake is initiated until the time when full pressure is built in the brake fluid. This time is usually about 300 ms for a normal car. The result of not simulating this is that the system shows about 5 units of percent higher reduction of fatality risk than it should (Rosén et al. 2010).

The distribution used to generate data for the variable driverBrakeDist is apparently not perfect as one can see in figure 16. These discrepancies are probably both due to the lack of data and that drivers' behavior in these situations is more complicated than our model. These discrepancies lead to other problems when fitting the generated collisionSpeed to the

# Appendix 1 – Cumulative distributions

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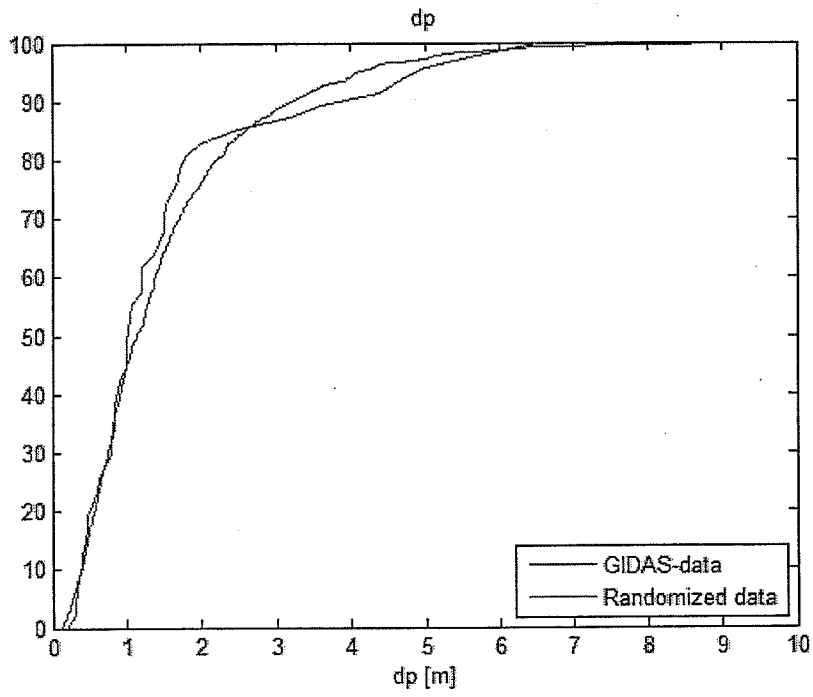


Figure 7. Cumulative distribution of  $dp$ .

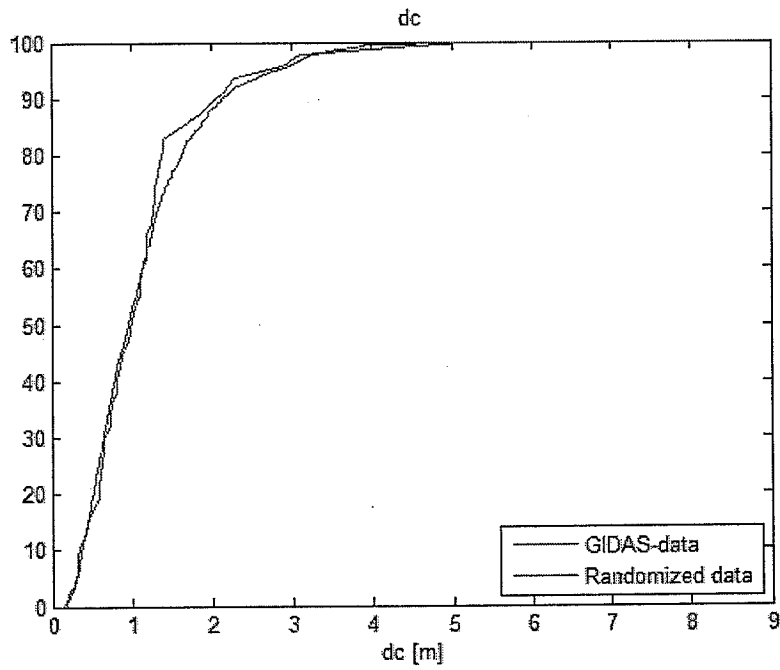


Figure 8. Cumulative distribution of  $dc$ .

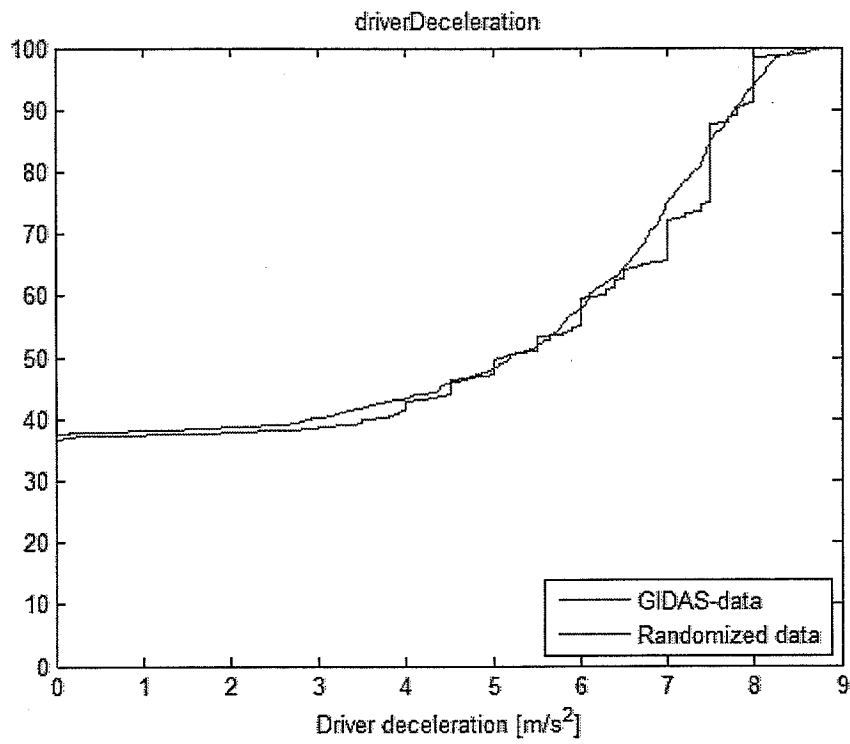


Figure 11. Cumulative distribution of driverDeceleration.

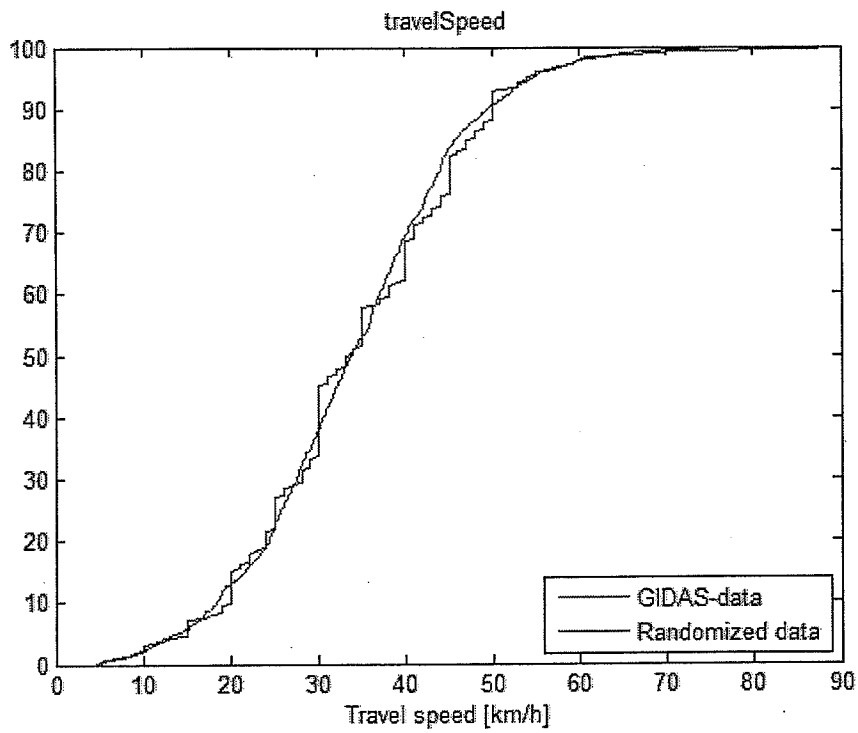


Figure 12. Cumulative distribution of travelSpeed.

## Appendix 2 - Test of system properties variations

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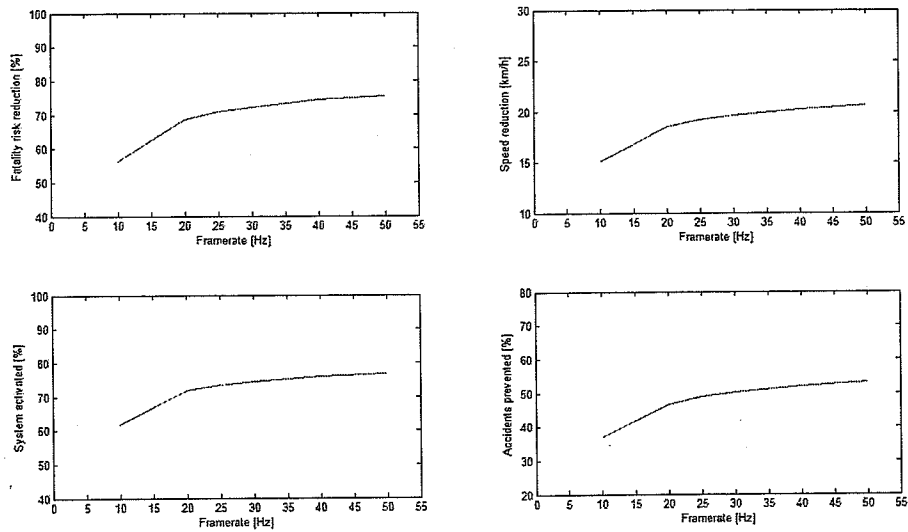


Figure 15. frameRate

As one can see in figure 1 the system's effectiveness does not increase more than about 5 percent when the frame rate is improved.

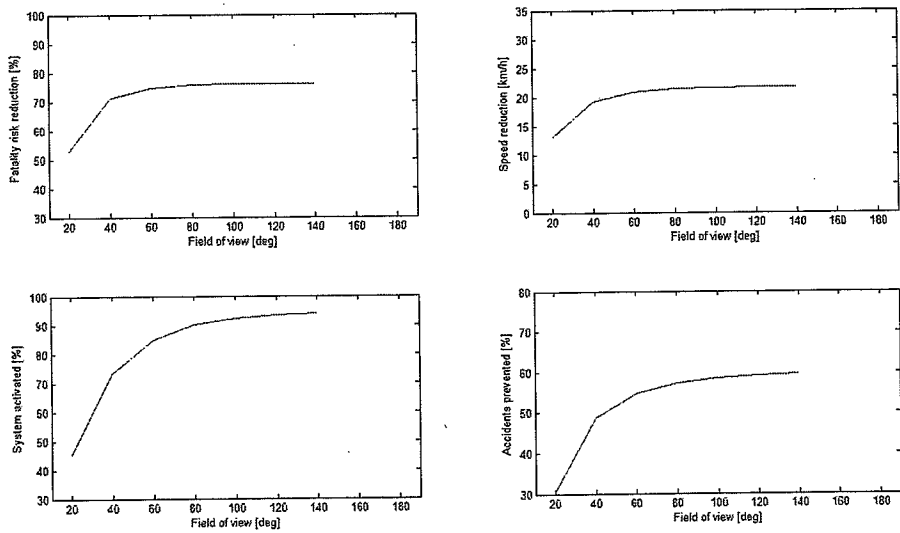


Figure 16. fieldOfView

The test in figure 2 shows that the system activates more often with a greater field of view. However this does not lead to any remarkable reduction in reduction of collision speed and

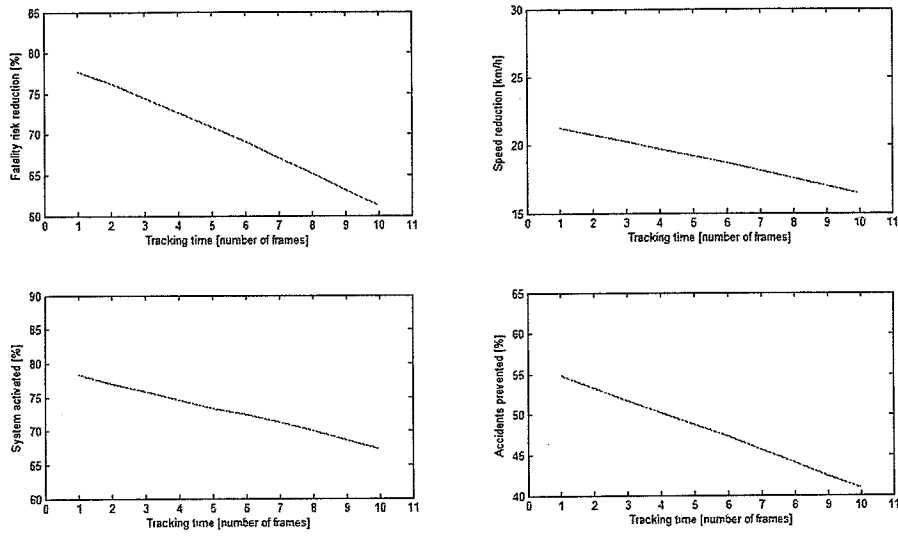


Figure 19. trackingTime

Figure 5 shows that the system's tracking time is a key parameter for increased effectiveness of the system.

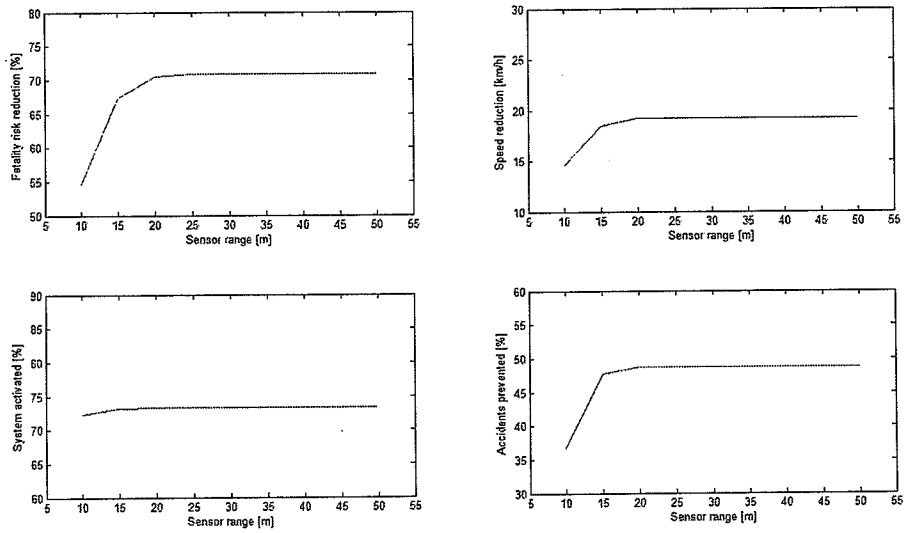
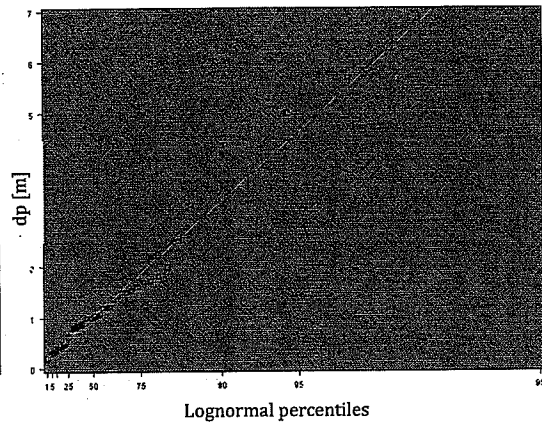
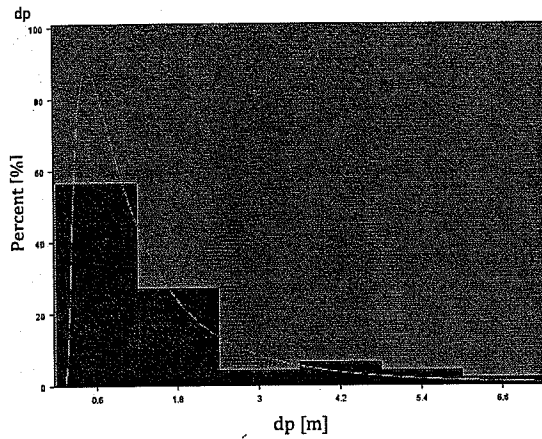


Figure 20. sensorRange

Figure 6 shows that there is little point in having a longer sensor range than about 25 meters.

# Appendix 3 – Distributions



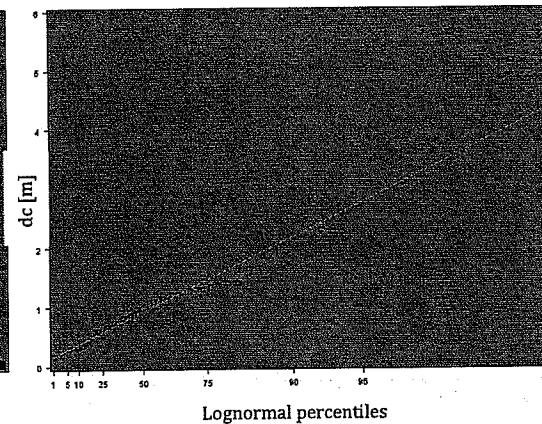
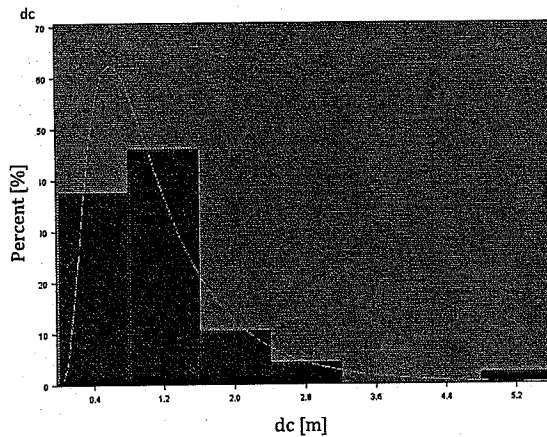
### Parameters for Lognormal Distribution

Parameter	Symbol	Estimate
Threshold	Theta	0.126201
Scale	Zeta	-0.10794
Shape	Sigma	0.979647
Mean		1.576712
Std Dev		1.841027

### Goodness-of-Fit Tests for Lognormal Distribution

Test	Statistic	p Value
Kolmogorov-Smirnov	D	0.09315345 > D > 0.250
Cramer-von Mises	W-Sq	0.05167607 > W-Sq > 0.250
Anderson-Darling	A-Sq	0.31741580 > A-Sq > 0.250

**Dp was represented by a lognormal distribution.**



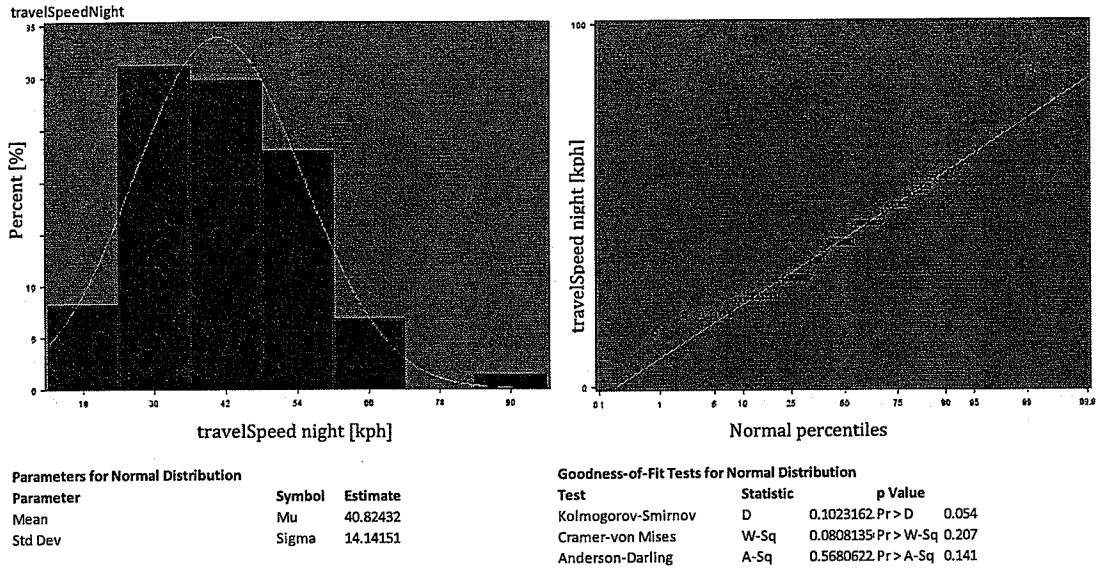
### Parameters for Lognormal Distribution

Parameter	Symbol	Estimate
Threshold	Theta	-0.0519
Scale	Zeta	-0.0198
Shape	Sigma	0.642366
Mean		1.153146
Std Dev		0.861244

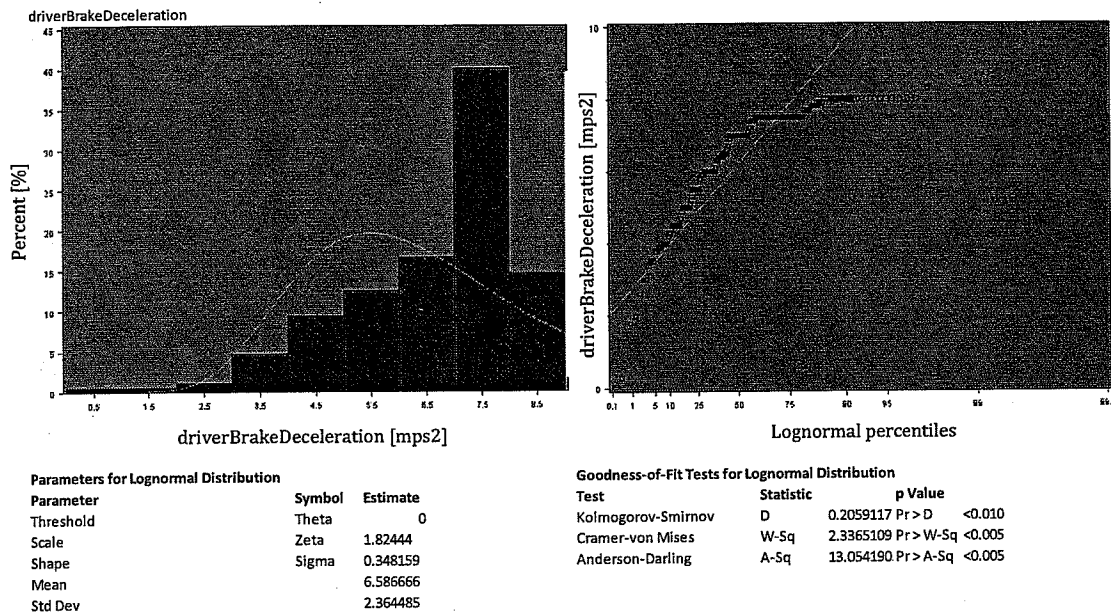
### Goodness-of-Fit Tests for Lognormal Distribution

Test	Statistic	p Value
Kolmogorov-Smirnov	D	0.1038371 Pr > D 0.129
Cramer-von Mises	W-Sq	0.0593527 Pr > W-Sq > 0.250
Anderson-Darling	A-Sq	0.3402820 Pr > A-Sq > 0.250

**Dc was represented by a lognormal distribution.**



This represents the normal distribution for travelSpeed during the night.



This represents the distribution for driverBrakeDeceleration. No fitted distribution was found for this dataset. Therefore the dataset were reflected by a factor 9 and a lognormal distribution was set up for it. This lognormal distribution is shown in the figure below.



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