ABSTRACT

Title of Thesis: DRIVER REACTIONS TO FORWARD COLLISION WARNINGS

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This study investigates driver behavior in terms of kept distance from obstacle, target-host velocity, change in speed, brake status and vehicle acceleration, after receiving Forward Collision Warning.

Data has been obtained from vehicles equipped with various sensors to monitor instantaneous vehicle performance and status as well as Connected Vehicle capability to communicate with Road-Side Units. Mobileye Forward Collision system is employed to detect obstacles in front of driver and communicate messages to driver as appropriate.

Results proved that drivers do not react dramatically after receiving warnings, instead, they tend to slow down a bit, keep longer distance to target and lower target-relative velocity to get the chance of better understanding of surrounding.

Furthermore, regarding to reaction time we found out that drivers react to such warnings on an average of 1.62 seconds which is significantly shorter than previous studies and can be considered an immediate response to the warnings.

DRIVER REACTIONS TO FORWARD COLLISSION WARNINGS

By

Hamed Emami

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Chapter 1: Introduction

Rear-end collision in which the front of the driver's vehicle crashes into another vehicle which is traveling on the exact same direction [1] is one of the most common crashes in the United States. To mitigate this issue, Forward Collision Warning Systems (FCWS) are developed which use various technologies to warn drivers in critical roadway incidents. Such systems used radar and/or cameras (vision-based versions) to identify obstacles in front of the vehicle and simultaneously use sophisticated algorithm to determine risk of crash; if the risk exceeds a threshold, the system warns the driver with the potential of identification of obstacle type and severity of the situation.

This study investigated on a FCWS, Mobileye, which is a vision-based Advanced Driver Assistance Systems (ADAS). This system collects information from the scene in front of the vehicle, and uses a series of algorithms to communicate measures and warnings to drivers as appropriate.

Vehicle instantaneous operating status is obtained from Connected Vehicle (CV) technology that collects data from equipped device and transfers via Dedicated Short-Range Communication (DSRC) to roadside equipment. This combination of ADAS and CV technology helps us to track drivers' behavior at any time during driving.

The goal of this study is to investigate drivers' behavior and reaction time based on the issuance of FCWs. As we will show through the methodology section of this thesis, since the exact time and type of warning is unknown, we assume that the one-time warning issues just at the moment of detection. Therefore, for fluency and simplicity purposes, we will use the word “warning” instead of “appropriate collision information” to show the new detection of a new obstacle, throughout this research.

The research hypothesis is that drivers' behavior and reaction time differs mainly based on the perceived collision time rather than sole warnings. In fact, what FWCS provide is just a hint to alleviate the distraction effect but still, drivers' reaction is mainly dependent on their perception of the situation.

In summary, this study aims to answer the following question by undertaking strategies to design appropriate sample:

1. How drivers respond after receiving FCW?
2. How sever each respond will be?
3. What is driver's reaction time in presence of FCWS?

Although there are many studies in this area, researchers have relied mostly on driving simulators and theoretical principals rather than actual driving performance. Driving simulator, though helpful in some cases, cannot represent real driving situations and thus analysis done on this basis may suffer from degrees of unreliability. This study targets this drawback and addresses related issues by focusing on real data collected by the state-of-the-art connected vehicle technologies in the United States.

Chapter 2: Literature review

Headway

The review of headway is of great importance in this study because as it going to be elaborated later in next chapter, in order to minimize the effect of driver's visual perception of roadway situation, we focus solely on warnings of far-away. What that means is we need to first find out what is the preferred headway kept by drivers (in general) and thereafter, this approximate will be used as optimum warning headway. To illustrate the concept, consider a driver who prefers headway of 2 seconds while driving. Within our design, warnings of around 2 seconds are best candidate to enter our sample rather than warnings of shorter or longer headways.

Time Headway (THW) is the time it takes between two consecutive vehicles to reach a point on the road [2]. This is a measure of distance between two following vehicle and is used in earlier versions of FCWS s.

The study of time headway helps to understand various transportation measures such as: estimation and evaluation of level of safety [3] [4] [5], analysis and implications on traffic operation [6] [7] and performance [8] as well as capacity evaluation [9] [10]. All these implies the importance and sensitivity of such investigations.

Headway is shown to be closely related to operation conditions like vehicle performance, traffic condition and level of service (surrogate safety measures, traffic conflict analysis, etc.). Safety studies also focus on headway as an important implication of travelers' safety since this has been a major cause of crashes. The importance of the issue can easily be understood by comparing the probability of crash between two driving behavior; following a vehicle holding a safe distance and tailgating. Rationally latter scenario does not give the driver a chance to brake on-time and dramatically increases the probability of having a crash.

Many factors affect time headway such as traffic volume, road conditions, weather, vehicle type and status, drivers' behavior and proportion of heavy vehicles [11]. Rossi, Gastaldi, and Pascucci [12] showed that the mean headway increases after an increase in percentage of heavy vehicles on the road which emphasizes on the principals of risk avoidance; since the consequences of having a crash with a heavy vehicle is much more severe than with a passenger car, drivers tend to behave more cautiously in vicinity of heavy vehicles. This behavior can also be related to the fact that drivers of heavy vehicles have less control over their vehicle (especially in higher speeds) and other drivers ought to keep extra distance from them in order to be able to avoid probable crash.

Generally, drivers adjust their headway based on their perception of overall driving condition and instantaneously keep safety distant from following vehicles. Such studies have an important implication: efficiency of vehicle brakes and stability system can tempt the driver to keep short headways.

Consistent with above-mentioned study, three main factors have been shown by Sanhita et al. [13]to play important role in the amount of headway kept by a driver; driver characteristics, vehicle features and specifications and traffic conditions. Adjustment of headway based on speed is also investigated by Brackstone et al. [8]; Just like what concluded by May [14], they showed an inverse relation, though limited, between speed and headway which indicates that in higher speeds drivers tend to keep longer headways maybe because in higher speeds the vehicle needs more time to respond against hazardous situations.

The effect of weather on amount of headway kept by drivers is also investigated by some researches; Alhassan et al. [15] showed that average headway decreases with an increase in the intensity of rainfall. This may be due to the fact that in intensive rainfalls visibility in roads decreases dramatically and drivers tend to decrease their speed and as mentioned earlier, in lower speeds shorter headway is expected.

Nevertheless, some other studies cast doubt in the ineffectiveness of rainfall on preferred headway; Rahman et al. [16] studied vehicles mainly travelling in two-lane rural state highways and inferred that rainfall does not have any significant impact on the mean headway kept by drivers. In order to justify this seemingly inconsistent result we need to find out in which condition each study was carried out. The less change in speed occurs, the less change in headway is expected.

Numerous models have been developed to estimate the THW in different traffic flow and other road and vehicle conditions. Among these models the most important factors affecting THW is shown to be portion of heavy vehicles on the road, vehicle speed, lane configuration, time of day and traffic volume [11]

Another research by Ayres [3] studying the driver behavior at different speeds and time-headways showed that on average drivers tend to keep between 1 and 2 second time headways even when situations do not push drivers to hold a tight spacing. However, this is well-below 3 seconds, recommended by most driving manuals. (e.g., California Driving Manual [17]).

This is consistent with the result of a study by Winsum [18] that THW is proved to be constant at different speeds (within drivers) but differs among people (between drivers). The drivers showed an average of THW as low as 1.4 sec to be able to avoid a rear-end collision. However, it should be noted that the results were tied with technologies and performance of vehicles at the time of investigation and now after passing almost seventeen years and emerging of new braking technologies with higher performance and stability, it is expected that drivers may choose to keep a bit shorter headway.

According to a study done by Moridpour [6], not only passenger drivers hold longer time headways in vicinity of heavy vehicles, but also heavy vehicle drivers themselves, tend to keep longer front THW because of both safety and operation limitations.

Although headway time of 2 to 3 seconds is recommended for safely driving behind a vehicle in front, in practice the headway time is often less than two seconds, especially at higher speeds [19]

There have been some studies investigating Time To Collision (TTC) as an indicator of drivers' perception of optimum moment to apply brakes especially in case of approaching a moving object. In fact, TTC shows the time it takes a vehicle to reach and crash into another vehicle if neither of drivers (following and target) change their vehicle velocity or path. In this, Horst [20] found out that drivers initiate brake between 1.3 to 1.8 seconds before reaching to the front vehicle.

However as mentioned earlier, vehicle technologies and its level of efficiency have great impact on driver perception of danger and TTC value. In other words, driving an "old car" rationally demands for higher level of driver's cognitive resources assigned to the environment and thus increases TTC [21].

In line with this finding, Kusano [22] found that drivers of high-tech vehicles tend to hold a lower value for TTC, since such state-of-the-art vehicles give drivers a feel of more confidence and reliability in case of hazardous conditions. This can free up cognitive resources in their mind and let them take timely actions to avoid a crash. Besides capability of auto braking and auto steering technologies, they found that drivers of such vehicles hold an average of 1.1 seconds for rear-end collisions, which is far less than what was recommended by most safety manuals. It is interesting to know that even in this lower average value, the crash rate of these vehicles is far less than conventional ones.

Driver behavior

Many studies investigated driver behavior after receiving FCW. It has been shown that this system helps distracted drivers to avoid crashes in many cases, especially when they fail to focus on road condition [23]. This was shown that a simple alarm or even a short beep can convey the message of warning to driver and help him or her to pay sufficient attention to the road.

On the other hands, many other researches cast doubt on effectiveness of such warnings; they actually tried to concentrate on helpfulness of such systems concentrating on the human factors and its effect on driver behavior. In other words, one of the most limiting factors has been shown to be human factors which should be addressed on first design level. [24] [25] . Lee et al. [26] also declares that technology advancement should be guided in a way that interaction between the system and driver reaches its maximum efficiency and reliability.

Lee et al. [27] showed that early alarms may lead drivers to react timelier and avoid crashes earlier. Nevertheless, many other argued that too early warnings can be considered as false alarm [28] [29] and generally can affect driver trust on system and lower perceived system performance [30].

The importance of this issue can be understood when driver receives too many alarms, even for targets too far away, when there is no need to take any action. In such situation, alarm is identified as an unreliable warning and driver response became questionable [31]. Conversely, late alarms do not have enough time to drivers to react appropriately and will diminish system reliability dramatically [32]. So, the main focus in designing FCWS should be on the system interaction with driver in a way that help driver take an appropriate action, on time.

Severity of driver reaction to the FCW is also shown to be a function of the way warnings are delivered to the driver. Although many studies showed that visual-audio [33] [27] and sole audio [34] warnings are effective in reduction of rear-end collisions, many other researchers [35] [36] declared that these modalities may not be optimal to deliver messages to the driver.

The reason for this claim is that in some cases the driver is already engaged with a distraction. Alternatively, visual warnings demand for attention to a display and compete with those required to avoid crashes. This is again why the way FCWS interact with driver is of great importance.

Regarding after brake onset, it is also shown that in both controlled and semi-real conditions, drivers tend to maximize brake power when their vehicle reaches a minimum distance to an obstacle [37] [38] [27]. This increase from brake onset toward maximum force is shown as a progressive process; meaning that as the vehicle reaches driver’s threshold distance, more brake force is applied step-wise.

To conclude the driver behavior against FCWS, it should be noticed that the effectiveness and reliability of system has an eminent effect of drivers’ trust and reaction after receiving warnings. In other words, the more reliable the driver finds the system, the more probable an appropriate reaction would be taken.

Reaction time

Reaction Time (RT) of a driver is the time interval between when driver is prompted for a hazard and the time, he/she takes a preventive action to avoid it [39]. RT concept has been repeatedly used by safety researchers and seems to be the main factor decreased due to distracted driving. Several researches especially regarding to brake responses demonstrated that Brake Reaction Time (BRT) is highly correlated with drivers' overall condition including cognitive loads and type of warnings received [27] [40] [41] [42] [43].

As mentioned earlier, distracted driving plays an important role in road crashes. Based on a study by Cicchino [44] almost 30% of all crashes happened in the US, were rear-end collisions in the year 2014. Furthermore, Highway Traffic Safety Administration (NHTSA) reported nearly 70% of rear-end crashes were due to distracted driving.

This huge effect of distracted driving on drivers' performance (especially in rear-end crashes), enticed researches to develop systems to draw drivers' attention to roadway incidents.

On the other hand, even if AEBS system couldn't avoid collision, it can reduce damage to both vehicle and driver/pedestrian, noticeably; based on a research done by The Highway Loss Data Institute which analyzes insurance claim trends and data, vehicles with this system were associated with 7-22% less damage liability and 4-25% less body injuries.

One of the main reasons for the success is that FCWS leads to lower collisions and quicker reaction time [45]. In fact, fastest reaction time allows drivers to keep safe time headway to avoid crash. This system also enables drivers to react promptly in case of sudden deceleration of front vehicle [46] by evaluating critical situation when the collision risk exceeds a threshold.

Reaction time is also shown to be a function of driver expectation and experience in similar cases; as demonstrated by Green’s review [47], RT is a value between 0.7 to 0.75 second when driver expects an event (such as merging lanes or yellow traffic light). This value increases for unexpected but common situations to1.25 second and as the worse scenario 1.5 seconds in the event of unexpected-uncommon event (such as sudden lane change).

However, these values cast doubt in finding of Summala [48], who concluded that in urgent situations, the BRT value can decrease to less than 1 second. This variation can be described by different brake efficiency among tested vehicles or simulators. Indeed, when driver perceives and trusts the high efficiency of brake system and stability of the vehicle in emergency conditions, he or she may react with a delay which is due to perceived ability of handling hazardous situation.

Drivers are also proven to react faster than what was proposed earlier, when urgency of lowering speed reaches a threshold [49]. They showed that people who pay more attention to the possible threat, not only react nimbler, but also initiate defensive braking which help them a lot to avoid crashes. This finding is consistent with FCWS performance assessments which relates that such warnings convey the concept of threat to drivers and push them to driver safer.

Chapter 3: Methodology

Data acquisition

The raw data for this study is obtained from Connected Vehicle Safety Pilot, a research program to investigate whether Connected Vehicles using DSRC technology are ready enough to be implemented in nationwide scale. The main purpose of this study is to investigate if safety features and technologies are effective in crash reduction to an acceptable degree without unnecessarily distracting motorists by their warnings and information conveyed.

The research started in August 2012 in Ann Arbor, Michigan and the data collected from the six-month Safety Pilot Model Deployment (SPMD). Study is performed along 75 miles of roadways with 26 roadside equipment along the network which are capable of commuting with equipped vehicles and other roadside equipment via DSRC.

Strategic locations have been chosen to place the most Road Side Equipment (RSE) such as freeways, signalized intersections and curves. This allows maximum coverage and reliability of data collected. Participating vehicles (as well as similar devices) are equipped with Data Acquisition Systems (DAS) enabling them to communicate with both RSE (Vehicle to Infrastructure - V2I) and other vehicles (Vehicle to Vehicle - V2V).

Figure 1 shows the overall layout of network as well as RSE equipment (DSRC-enabled) locations.

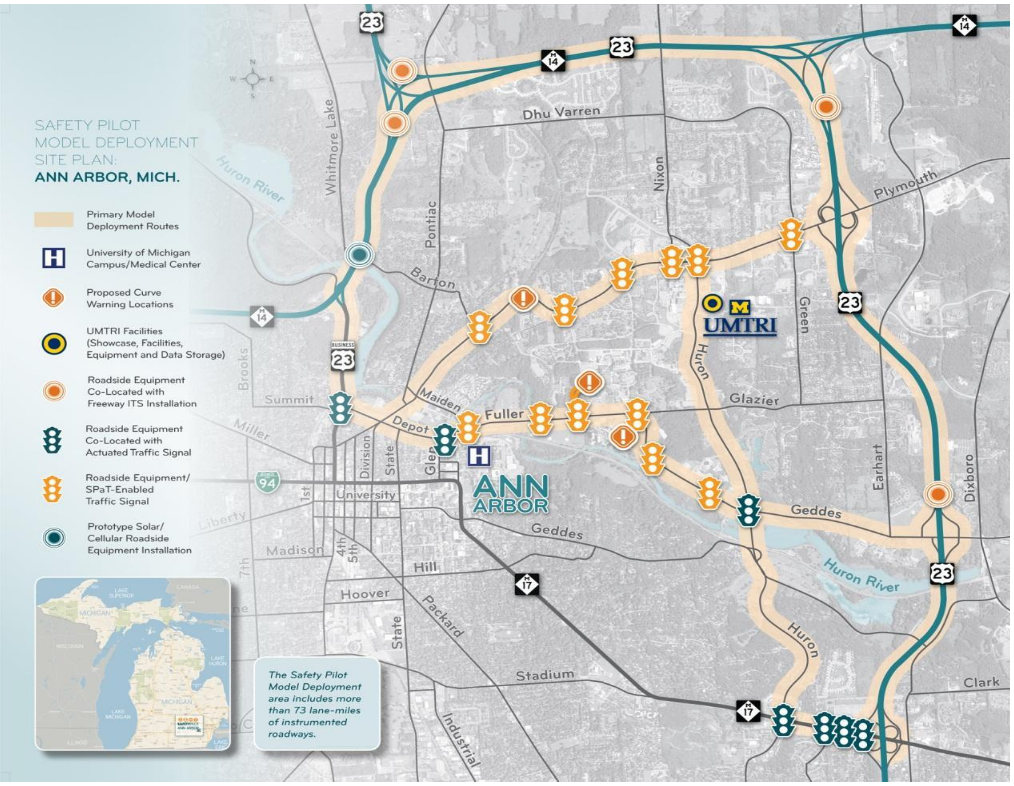

Figure 1 : Safety Pilot Model Deployment Site Plan, Ann Arbor, Michigan

One of safety applications of this research is Forward Collision Warning System (FCWS) which uses Mobileye system to identify vehicles in front of driver, estimate the collision risk and communicate measures and warnings to drivers as appropriate. This research is going to analyze data populated from Mobileye vision-based Advanced Driver Assistance Systems in order to identify driver behavior in the presence of a FCWS.

Mobileye System

Based on the information on the Mobileye's official website, the Mobileye system is designed to give collision warnings when it detects an obstacle, either a vehicle or a pedestrian, near the driver's vehicle. The system used sophisticated algorithms to determine the total risk and issues alarm only when there is imminent risk of collision regardless of target's position. Generally, the warnings (especially for vehicle obstacles) are issued with maximum TTC of 2.4 seconds which gives the driver enough chance to avoid collision. Furthermore, the system works based on THW concepts which enables timely pedestrian alerts. The basic metrics, speed and distance to target for such calculations are provided by the sensors embedded in the system and is calculated constantly enabling the system to issue timely alerts.

Mobileye system consist of a gadget mounted of dashboard, in front of driver and gives timely visual and sound alerts, easy for driver to get informed with minimum distraction. Figure 2 shows the pedestrian warning when it's at high collision risk (icon in red).

Figure 2 : Forward Collision Warning of passing pedestrian

Moreover, this system warns if an obstacle is in other lanes but still at risk of collision. This is because of the fact that that even vehicles in adjacent lanes have crash potential in some circumstances. Described condition is shown in Figure 3 and 4 where the warning is still in green phase since the collision risk has not reached its critical value.

Figure 3 : Forward Collision Warning of adjacent vehicles

Figure 4 : Forward Collision Warning of adjacent passengers

Based on the data we have from DAS, the available files are as presented in table 1;

1. Data obtained from Mobileye system logging data from obstacles in front of vehicle and detailed analysis of type, position, distance, etc.

2. Data accumulated from onboard WSU system which presents detailed status of vehicle at cent-second intervals.

Table 1: Data Elements of the study

File Name	**Description**	**Sample Rate**
DataFrontTargets	Log of the data collected by the Mobileye sensor which is a part of the DAS; largely includes data about the (vehicle) object that is in front of the host vehicle	10Hz
DataWsu	Log of GPS and CAN Bus data obtained via the onboard WSU	10Hz

DataFrontTargets File

Data in DataFrontTarget file is prepared and collected by Mobileye system which, as mentioned earlier, is a vision-based system which collects data from the front of vehicles and after analyzing by sophisticated algorithms, makes appropriate decision on how and when to communicate with the driver via non-distractive channels. Output will be visual and sound warnings helping the driver take course of action to avoid collision.

Table 2 describes field populated by Mobileye sensor which are embedded in DataFrontTarget file.

Table 2 : Data Elements of the DataFrontTargets File

Field Name	Type	Units	Description
Device	Integer	none	Unique number to identify each device installed on vehicles.
Trip	Integer	none	number of ignition cycles (defines as when engine starts till it kills)
Time	Integer	cent seconds	Instantaneous time starting when DAS starts to work (when the ignition is on "ON" position)
TargetId	Integer	none	Numeric ID assigned by the Mobileye sensor to distinguish between the different objects being tracked; the closest obstacle is given a TargetId value of 1
ObstacleId	Integer	none	ID of new obstacle, as assigned by the Mobileye sensor, and its value will be the last used free ID
Range	Integer	m	Longitudinal position of an object, typically the closest object, relative to a reference point on the host vehicle, according to the Mobileye sensor
RangeRate	Real	m/sec	Longitudinal velocity of an object, typically the closest object, relative to the host vehicle, according to the Mobileye sensor

Field Name	**Type**	**Units**	**Description**
Transversal	Real	m	The lateral position of the obstacle, as determined by the Mobileye sensor
TargetType	Integer	none	Classification of an identified obstacle/target as a car, truck, pedestrian, etc.
Status	Integer	none	Classification of the motion (kinematic state) of an identified obstacle/target as stopped, moving, etc.
CIPV	Integer	none	Field communicating whether an obstacle is the closest in a vehicle's path

There are some elements in Table 2 which represent different numbers with different meanings. Table 3 shows their enumerations.

Table 3: Enumeration Table for DataFrontTargets File

Data Element	**EnumId**	**Value**	**Name**	**Description**
TargetType	409	0	Car	Mobileye sensor has identified an obstacle/target as a car
		1	Truck	Mobileye sensor has identified an obstacle/target as a truck
		2	Motorcycle	Mobileye sensor has identified an obstacle/target as a motorcycle
		3	Pedestrian	Mobileye sensor has identified an obstacle/target as a pedestrian
		4	Bicycle	Mobileye sensor has identified an obstacle/target as a bicycle

Data Element	**EnumId**	**Value**	**Name**	**Description**
Status	410	0	Undefined	Mobileye sensor is unable to determine the kinematic state of the identified obstacle/target
		1	Standing	Mobileye sensor has determined that the identified obstacle/target is standing
		2	Stopped	Mobileye sensor has determined that the identified obstacle/target is stopped
		3	Moving	Mobileye sensor has determined that the identified obstacle/target is moving
		4	Oncoming	Mobileye sensor has determined that the identified obstacle/target is oncoming
		5	Parked	Mobileye sensor has determined that the identified obstacle/target is parked
		6	Unused	Value saved for future assignment
CIPV	1	0	False	Identified obstacle/target is not the closest in a vehicle's path
		1	True	Identified obstacle/target is the closest in a vehicle's path

Vehicle status

The second table we use as raw database for our analysis is called DataWSU. The data consists of the vehicle's Controller Area Network (CAN) Bus as well as GPS-based data. Most of these elements are those collected from vehicle performance information system which logs detailed information (such as brake, signal lights and speed and heading) from either its sensors or vehicle's central processor system. Table 4 is a thorough list of fields in this file with a brief description of each.

Table 4: Data Elements of the DataWsu File

Field Name	Type	Units	Description
Device	Integer	none	Unique number to identify each device installed on vehicles.
Trip	Integer	none	number of ignition cycles (defines as when engine starts till it kills)
Time	Integer	Centisecond	Instantaneous time starting when DAS starts to work (when the ignition is on “ON” position)
GpsValidWsu	Integer	none	Communicates whether a GPS data point is valid or not
GpsTimeWsu	Integer	millisecond	Epoch GPS time received from the remote vehicle that has been targeted by the host vehicle’s WSU
LatitudeWsu	Float	deg	Latitude from WSU receiver
LongitudeWsu	Float	deg	Longitude from WSU receiver
AltitudeWsu	Real	m	Altitude from WSU receiver
GpsHeadingWsu	Real	deg	Heading from WSU GPS receiver
GpsSpeedWsu	Real	m/sec	Speed from WSU GPS receiver
HdopWsu	Real	none	Horizontal dilution of precision
PdopWsu	Real	none	Position dilution of precision
FixQualityWsu	Integer	none	GPS Fix Quality

Field Name	Type	Units	Description
GpsCoastingWsu	Integer	none	GPS Coasted
ValidCanWsu	Integer	none	Valid Vehicle CAN Bus message to WSU
YawRateWsu	Real	deg/sec	Yaw rate from vehicle CAN Bus via WSU
SpeedWsu	Real	kph	vehicle speed received from CAN Bus
Brake	Integer	none	Brake position; presented in percent communicating displacement of brake from its default position to maximum displacement during a trip
AxWsu	Real	m/sec2	Vehicle acceleration
PrndlWsu	Integer	none	transmission status
VsaActiveWsu	Integer	none	Stability control active from vehicle CAN Bus via WSU

With regard to research questions, we first would identify the exact time when driver receives a new warning for a new obstacle (which may be vehicle or pedestrian) and by matching the event with the relevant data from WSU file (which shows the vehicle status) we would be able to identify any changes in vehicle status. This procedure shows how driver reacts when he/she receives any information from front environment of vehicle.

Sample selection

Assumptions

To select our sample from numerous data log available (almost 80 million logs), first we need to define what our assumptions are and then design an appropriate algorithm which can extract appropriate data from raw data.

The point is that from the logged data, although we know the exact time of each detection, we do not know when the warnings are issued and even if any warning is delivered to the driver. However, the drivers get to know when they are in danger zone and once they knew that, they react cautiously to avoid probable danger. In fact, drivers receive warnings of various priority and since our study is limited to targets with TTC of 2 to 2.4 seconds, they receive low priority warnings/information which convey the sense of probable danger. Drivers then are expected to react to this, by taking a caution (or preventive) reaction.

However, to describe the whole process with more fluency and simplicity, this detection of obstacles (even though the status of warnings is unknown) will be mentioned as "warning" throughout this research.

So, when we say reaction to warning, it means driver's reaction after getting notified about a potential hazard, not necessarily receiving a specific warning.

Since our main database contains continues Forward Collision data, unless for close targets, high priority warnings, we assume that the system delivers warnings to the driver only in the moment of identifying a new obstacle. In other words, warnings for far-away objects are assumed to be issued only for a short time after identification, rather than in continues manner.

To illustrate this assumption, consider a target at TTC of 2.2 seconds identified in third second of driving. Our assumption is that the system issues a one-time warning for this obstacle, while tracing its risk factor. Only if the target gets closer and the risk factor reaches a threshold, the system starts to warn with a higher priority pattern.

Furthermore, our database neither include any data explaining the situation under with the warnings were issued, nor data showing the severity of issued warning. In other words, based on the collected data it is not possible to find out when and what type of warning (in term of warning severity) our driver receives in a specific situation. Knowing this, can alternate the final outcomes as driver behavior depends on the type of warning received. To illustrate this issue, compare two situations; in the first situation, driver receives visual warning with a single "beep" for warnings with TTC of 2.4 seconds and in the other scenario driver receives a sound warning with higher frequency (besides visual warning) for TTC of 2 seconds. Rationally, driver should react differently in these two situations, however because our database does not distinguish between these two warnings, we assume that all warnings between 2 and 2.4 seconds are delivered in the same manner.

In short, the to design our sample, we filter out the following data in order to not only simplify the analysis procedure, but also to minimize errors and unwanted records in our sample;

1. Records with repetitive Obstacle IDs
2. Records with Target IDs other than 1
3. Records for TTC of outside the range of 2 to 2.4 seconds
4. Records with invalid data in it
5. Records with extreme data

Procedure

In order to analyze THW and RT right after receiving a new warning by Mobileye, we first need to identify the moment a new obstacle is sensed. The criteria we used to determine this first identification of an obstacle, is simply changes in Obstacle Id filed. According to metadata presented in table 2, whenever a new target is identified, the last free ID is assigned to it. Thus, the first record of a new obstacle ID is the exact moment a new obstacle is sensed by the system.

The next step is to choose sample logs before and after this moment; the logic behind this, is that comparison of driver's behavior before and after receiving a new warning gives an idea of how drivers are affected by FCWs. Furthermore, since RT and THW (and even TTC) values have been shown by previous studies to be less than three seconds, our analysis limits to three seconds before and after issuance of new warning to cover enough time interval for a precise analysis. This upper limit of time interval allows us to avoid missing any late reactions due to probable distraction, driver characteristics, and unfamiliarity of driver with the system performance.

This procedure is a bit tricky because not all obstacle detections can lead to a meaningful warning which should be given to the driver. In other words, from a broad range of detection and numerous obstacles detected, only warning for the vehicles with high risk of collision is identified as a candidate of FCW to be commutated with the driver. In order to select only these warnings, an extra criterion is added to the procedure; selected detection should be assigned target ID of "1". This ensures that relevant obstacle is closest to driver and thus appropriate warning is to be delivered to driver. Figure 5 shows the procedure steps.

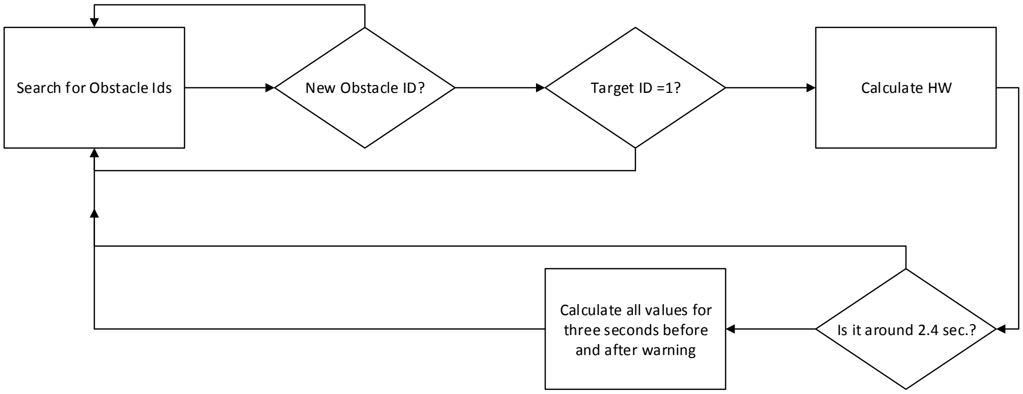

Figure 5: Sample Design flowchart

Another factor which plays an important role in reliability of results is “driver perception of danger”; in other words, do drivers react solely based on what they see on the road scene or besides that, receiving a warning can induce a sense of danger in their mind? Obviously, it is impossible to completely eliminate the effect of drivers’ visual sense, however to minimize its effect and focus more on impact of warnings, we made a heuristic assumption; only targets that are far enough are considered in analysis to minimize the effect of instantaneous reaction of driver. By doing so, the analysis concentrates on drivers’ reaction to FCWs at moments when there is enough time to make a rational decision.

For this purpose, we calculated the amount of headway for each record and filtered out warnings issued for close targets. Based on the literature review, the amount of normal headway kept by majority of drivers has been shown to be somewhere between 2 and 3 seconds and thus in this study, we consider headways around 2.4 seconds as far-away. This filtration of close objects lets us to limit our analysis to objects for which driver trust on warning rather than visual sense.

The sample collection process concludes with matching logs extracted from front target file with corresponding entries from WSU database. The field we consider here are “Device ID”, “Travel ID” and “time”; device ID is a unique number assigned to each device installed on vehicles, Travel ID is a unique number assigned to each travel immediately after each engine start and finally elapsed time is the amount of time passed after ignition is in “ON” position. The combination of Device ID, Travel ID (driver ID) and elapsed time gives a unique index to each entry which we use to match entries from two files. The sample, after clearing procedures, contains data from 91 vehicles, 611 drivers and 13, 298 warnings which demonstrates a large data set.

Sample design limitations

Like any other study, the current investigation has its own limitations which we would like to categorize into two main levels; Data collection and Sample selection.

The most important issues in data collection are sensor, transmitters and receivers failures. As discussed earlier there are some entries with either no data in it or even wrong recorded data; for instance, steer angel and brake values are missing in many records which forced us to eliminate the whole record. Furthermore, some recorded values (due to sensor errors) seems to be wrongly recorded (like negative speed). For example, data received by the central server shows odd values, vehicle speed drops from 50 kilometers to near zero in less than 2 seconds without applying brakes.

During sampling procedure, we focused solely on warnings for far away target to minimize the effects of direct-road-condition decisions while maximizing the effects of warning system on driver behavior. This elimination of near-range warnings may cast minor inaccuracy on our results

Chapter 4:Analysis

Analysis Of Variance (ANOVA) is usually used in such researches to determine the general behavior of drivers within research sample. In this research, the independent variable is receiving a new warning which acts as a proxy of the presence of an obstacle (whether vehicle or pedestrian) in front of the driver. Dependent variables for analyzing driver reaction are range, range rate, speed, brake pedal position and vehicle acceleration. Reaction Times are calculated based on the first time the driver applies brake after receiving a warning;

$$\text{RT} : \text{First change } (\Delta \text{B}) \tag{1}$$

Where:

RT: Reaction time

ΔB: change in brake pedal position

Furthermore, we investigate how drivers adjust their time headway after receiving warnings.

For this purpose, to choose appropriate entries for our sample we need to calculate headway for each single warning and filter out warnings of near obstacles. Headway is therefore calculated by the following equation:

$$\text{HW} = \frac{\text{R}}{\text{V}} \tag{2}$$

Where:

HW: Headway

R: distance (in meter) from obstacle measured by Mobileye sensors

S: speed (in meter per second) of the vehicle measured by mounted GPS

Results

Driver Reaction

We applied ANOVA to our sample based on the time a new obstacle identified as our independent variable and five types of reaction as dependent variables; Range, Range Rate, Status, Speed, Brake Pedal Position and Acceleration. This analysis is performed to understand whether change in value of each dependent variable value can be attributed to the issuance of warnings.

All these variables are calculated based on a 3-second interval before and after receiving a new warning. Range demonstrates the distance between host and target vehicle and is measured in meter). Moreover, Range Rate measures the velocity of the target relative to the host vehicle and is measured in meter per second (m/s)). Speed values are collected by vehicle CAN Bus system and shows instantaneous speed of vehicle in kilometer per hour (KPH Brake pedal position shows the percentage of total available brake force applied by driver and can get a values between 0 and 1 (0 when brake is not active and 1 when brake pedal is pushed all the way down) and finally the last dependent variable is acceleration which shows the longitudinal acceleration of the host vehicle and is measured in meter per square second (m/s^2).

The output of ANOVA, which is presented in table 5, indicates that since the analysis on all dependent variables (first column) has led to the p-value of less than 0.05, they are all correlated to the issuance of FCWs. It means that changes in these variables after receiving warnings can be attributed to the warning itself. For example, the distance to the target (range) changed after receiving FCWs.

Table 5: Analysis OF Variance

Dependent Variables	**Independent variable**	**F**	**Sig.**
Range	issuance of FCW	9.910	0.002
Range Rate		171.188	0.000
Speed		76.311	0.000
Brake pedal position		5.621	0.018
Acceleration		5.291	0.021

Now that we showed the impact of warnings on our dependent variables, we need to know how much these factors have been changed after drivers received warnings. In order to answer this question, descriptive analysis should be applied on through the sample, before and after receiving warnings. The result of descriptive analysis is summarized in Table 6. T-tests were conducted to find the mean difference between the before and after warning issuance (Table 7).

Table 6: Descriptive Analysis

Dependent Variables	**Area**	**Mean**	**N**	**Std. Deviation**	**Std. Error of Mean**	**Minimum**	**Maximum**
Range	Before FCW	46.939	13298	35.476	0.308	1.722	157.125
	After FCW	48.247	13338	32.230	0.279	1.317	159.001
Range Rate	Before FCW	-0.186	13298	3.605	0.031	-29.984	25.063
	After FCW	-0.823	13338	4.312	0.037	-36.686	18.463
Speed	Before FCW	70.193	13298	37.434	0.325	10.003	144.282
	After FCW	66.168	13338	37.767	0.327	5.008	138.906
Brake pedal position	Before FCW	2.836	13298	11.927	0.103	0.000	64.000
	After FCW	3.191	13338	12.507	0.108	0.000	64.000
Acceleration	Before FCW	-0.001	13298	0.550	0.005	-3.600	3.087
	After FCW	-0.017	13338	0.574	0.005	-3.280	2.550

The first column of Table 6 shows all dependent variables, second shows the area (time) of calculations which can be before or after warnings. The most important column, column three, presents mean values for each variable before and after FCWs. The other columns calculate some statistical values through the sample.

Table 7: comparison of means before and after FCW (T-test)

Row	Variable	Sig.
Pair 1	Range-before/after warning	.000
Pair 2	Rate - before/after warning	.000
Pair 3	Speed - before/after warning	.000
Pair 4	Brake - before/after warning	.002
Pair 5	Acceleration - before/after warning	.000

Furthermore, according to the Table 7, all five variables have significantly change due to the issuance of warnings, meaning that even minor change in average of one variable (before and after warning) should be considered as a meaningful change due to the driver perception of the situation.

The distance to the target is shown to be approximately 47 and 48 meters per second for before and after warnings (Figure 6). This shows that although drivers tried to keep longer distance from targets, this was not a radical behavior (while the change is still significant); in other words, warnings led drivers to keep just a bit longer distant from targets.

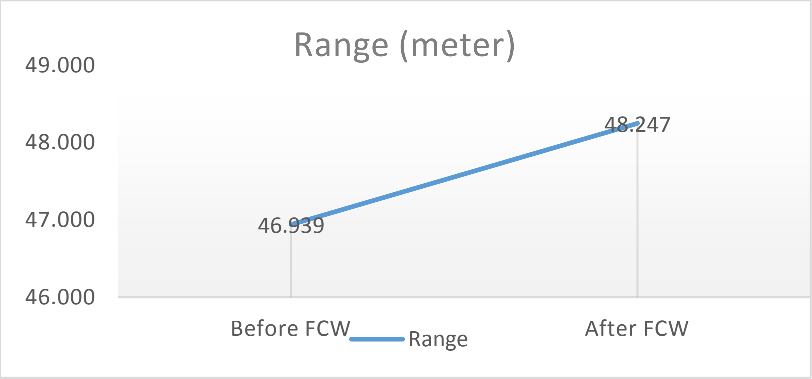

Figure 7 distance to target before and after FCW

On the other hands, the velocity of the target (relative to the host vehicle) showed a significant change from -0.1 m/s to -1 m/s (Figure 7). This can be described as driver decreases vehicle-target velocity. This can be due to either applying brake or releasing throttle a bit.

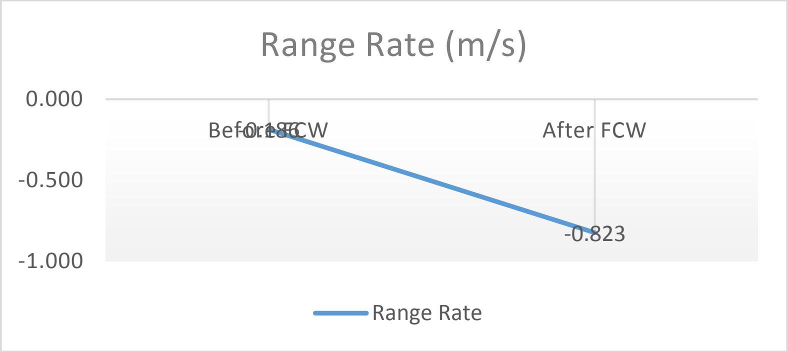

Figure 7: host-target relative velocity before and after FCW

Furthermore, as expected, speed of the vehicle before and after warnings showed a significant change from 70 to 66 meters per second, respectively. This is consistent with mentioned results as increase in speed can cause longer range and lower range rate. Figure 8 shows this fact, graphically.

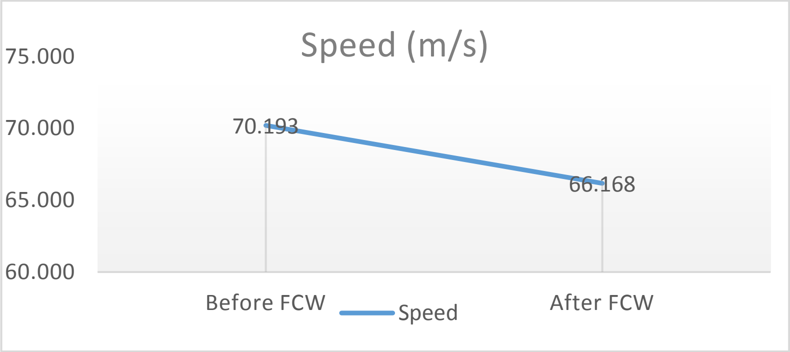

Figure 8: speed of host vehicle before and after FCW

Brake pedal position and acceleration, though correlated to the issuance of warnings, again demonstrated significant change from 2.8 to 3.1 percent for brake position and from -0.001

to -0.012 meters per square second for acceleration, before and after warnings respectively. Figure 9 and 10 show changes in average of these variables before and after FCW.

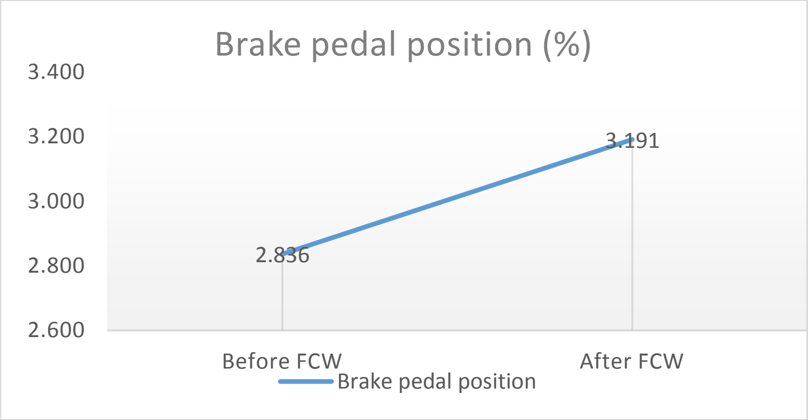

Figure 9: Brake pedal position before and after FCW

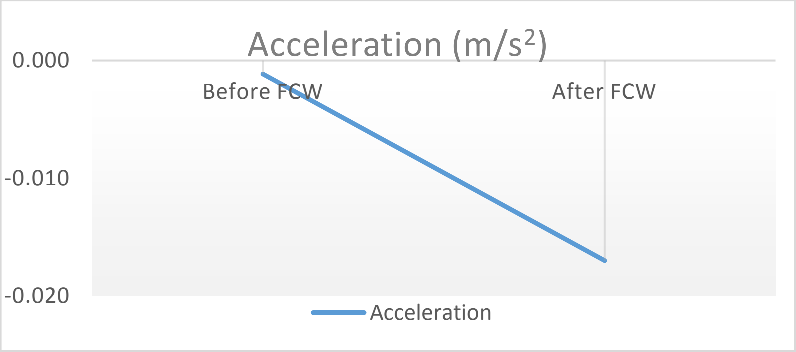

Figure 10: host vehicle acceleration before and after FCW

The results have a common implication; drivers do not usually react radically after getting notified of warnings by the FCWS, instead the system induce the sense of potential danger to them and causes them more alert while driving. This reaction seems to be more in form of minor slowdowns and keeping longer distance from the target. Although throttle data is not available in our database, it is speculated that since the change in average brake applied is minor, the major reaction after receiving warnings is through loosening throttle rather than applying brake, in most cases.

Reaction time

Regarding the analysis of reaction time, as mentioned earlier, we consider time elapsed from issuance of a warning when driver shows a reaction for the first time. Similar to the previous analysis, a three-second time frame interval (after issuance a new warnings) is considered for analysis of drivers' first reaction.

The analysis showed that majority of drivers react within a second (32%), while 15% and 14% of drivers reacted within 1 to 1.5 and 1.5-2 seconds, accordingly. Finally, the rest reacted more than two sec. which are considered as extreme data.

As shown in Table 8, drivers' reaction time has the minimum and maximum value of 0.10 and 3.00 seconds respectively, which demonstrates the range of reaction time showed by drivers at various driving situations. The average value of drivers RT is 1.62 seconds which is considerably shorter than what was assumed.

Table 8 : Reaction Time

	N	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
RT	579	10.00	300.00	162.1071	85.48082

Discussion

Several insights into drivers' reaction after receiving an FCW is provided by the present study. The results indicated no radical changes in driver behavior due to forward collision system. In other words, drivers do not decide solely based on the warnings they receive from the system. This is mainly because they rely on their visuals and other senses (like hearing) on a higher priority comparing to the system warnings. Thus, it can be inferred that such warnings improve driver behavior and reaction in the case of existing distracting factor or any other cases in which driver fails to react timely.

Another important finding is the way drivers react immediately after the system identifies a new obstacle and informs them. Based on our findings and as mentioned before, drivers do not usually react sharply against FCWs; instead they just pay extra attention and caution to the condition by light brakes to just maybe give themselves extra time to search for surroundings and enhance their cognitive response.

Even though majority of drivers react to FCWs within a second, the mean value for brake reaction time was 1.62 seconds which is a bit less than what calculated by previous studies.

Chapter 5: Summary and conclusion

Unlike majority of previous studies on the drivers’ behavior against Forward Collision Warnings, this study was designed based on data obtained from real driving performance. State-of-the-art technologies are utilized to record and communicate vehicle and driver performance in order to provide data with ultimate reliability and precision.

This study analyzed the data collected by Safety Pilot project, which was equipped with several vehicles with connected vehicle technology. The project provided vehicle performance data as well as data generated by safety systems designed to warn drivers about obstacles in front of vehicle. We specifically focused on data generated Mobileye forward collision system, which detects, analyzes and conveys messages to drivers enticing them to decide better while driving. Sensing obstacles is on visual basis and the system is capable of identifying obstacle type (car, truck, bicycle and pedestrian) as well as its status (stopped, moving).

Data collected from connected vehicle technology needed to be cleaned prior to analysis. This is mainly because of two main issues: sensor failure and communication difficulties.

Generating the database was the next challenge. Not all warnings are good candidates for the analysis, we had to choose warnings of obstacles far enough to reduce the effect of natural-immediate visual driver reaction. To do so, we focused solely on warnings issued for obstacles of optimum headway, based on previous studies on this issue.

Analysis are mainly concentrated on drivers’ types of reactions after getting warned by the system warnings. Issuance of FCW is considered as independent variable against five dependent variables; range, range rate, speed and acceleration. This design enabled us to perform an ANOVA to see how driver reaction (dependent variable) are affected by FCW (independent variable). Thereafter, average of values is compared within three seconds before and after warnings to investigate the severity of each reaction type.

Our database did not include any data for determination of warning time, type and severity. Thus, we assume that there is one-time warning which is issued just at the moment of detection. Moreover, for simplicity and fluency of the context, we used the word “warning” instead of “appropriate collision information” to show the new detection of a new obstacle, throughout this research.

Analysis showed significant p-values for all dependent variables which emphasized on effectiveness of the FCWS on driver’s behavior. Moreover, it was concluded that drivers do not react dramatically against such warnings; instead, they try to stay away from danger or even correct their driving behavior. Surprisingly it proved that drivers do not apply harsh brakes or even avoid brake (in many cases) after receiving warning and even though throttle data is not available to this study, it is guessed that drivers release the gas pedal a bit just to reduce speed and distance to target in order to reserve more time to take an appropriate action.

This pattern of reaction is in line with the expectations, simply because the warnings (information) are related to far-away targets with the lowest priority and rationally for such class of frequent warnings drivers do not usually react radically. Indeed, in the mentioned situations drivers were showed to take cautious actions to get ready in case danger becomes more imminent which needs their imminent and radical reaction.

Finally, we showed that majority of drivers react to warnings rather quickly (less than a second) and this shows the importance of warnings to driver. In other words, driver believe in accuracy and reliability of warnings and thus react in no time (at least in form of sudden light braking). However, the mean value for reaction time calculated as 1.62 seconds which can be due to the low priority of issued warnings.

Huge sample size, timely and precise performance data are our competitive advantage against previous studies which have relied solely on driving simulator data with less sample size and expectation of representation of real driving conditions.

This research can be used as a source for researchers who are going to present enhanced FCWS design s such as collaborated FCWS and adaptive FCWS. Based on our results, drivers should trust on the system and find it reliable enough in order to react promptly and unless a warning system does not address efficient interaction with driver, the system won’t reach its maximum potential in avoidance of crashes.

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