Wireless Local Danger Warning: Cooperative Foresighted Driving Using Intervehicle Communication

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***Abstract*—Vehicle collision mitigation, cooperative driving, and vehicle-to-vehicle (V2V) and/or vehicle-to-infrastructure (V2I) communication constitute a broad multidisciplinary research field that focuses on improving road safety. Statistics indicate that the primary cause of most road accidents is vehicles' excessive speed and delayed drivers reaction. Thus, road safety can be improved by early warning based on V2V communication. An innovative system called wireless local danger warning (WILLWARN), which is based on recent and future trends of cooperative driving, enables an electronic safety horizon for foresighted driving by implementing onboard vehicle-hazard detection and V2V communication. One of the key innovative features of the proposed system is the focus on low penetration levels in rural traffic by a new message-management strategy that is based on storing warning information in the vehicle and distributing warnings through communication, particularly with oncoming traffic. The system timely warns the driver about a dangerous situation ahead by decentralized distribution of warnings and incident messages via ad hoc intervehicle communication. The WILLWARN system is based on a modular object-oriented architecture consisting of the V2V communication module (VVC), the warning message-management module (WMM), the hazard-detection-management module (HDM), the hazard-warning-management module (HWM), a Global Positioning System (GPS) receiver, and various onboard sensors. In this paper, all system modules, as well as their interoperability, are presented in detail.**

***Index Terms*—Ad hoc wireless network, collision avoidance, cooperative systems, foresighted driving, vehicle-to-infrastructure communication, vehicle-to-vehicle (V2V) communication.**

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I. Introduction

THE development of vehicle-collision-warning systems that detect oncoming collision dangers and provide warning messages to the driver has become, particularly over the past decade, a very important research field and application area. A significant amount of the proposed systems is based on information that is individually collected by each vehicle using radars [1], [2] and other types of sensors [3]–[5]. The data elicited from vehicle onboard sensors usually provide information regarding the relative position, speed, and motion between the detecting vehicle and the moving or stationary obstacles, which is then processed to determine both the probability of a collision and a time estimation of a collision. Such commercial systems already exist in the market [6], [7] and mainly hold to the concept of autonomous collision warning.

Over the last decade, an alternative approach known as cooperative driving has appeared, introducing a very active research area (e.g., [8]–[11]) based on vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communication. More specifically, this new scenario of collaborative driving lies in the fact that the vehicle or the infrastructure can communicate its location and other information to surrounding vehicles or nearby infrastructure. In this case, the collision warning is intended by incorporating the information communicated from the surrounding vehicles into the warning decision-making process.

While the early cooperative driving concept was researched in automated highway systems [12]–[14], the concept of cooperative driving is being recently adapted to broader applications (e.g., cooperative adaptive cruise control [15], [16], cooperative intersection safety systems [17]–[19], and other collision warning systems [20]–[22]), as well as to scenarios where information is communicated between vehicles and nearby infrastructure, e.g., intersection or roadside traffic controllers [23]. Recent advances in wireless communication systems and the fact that GPS has become common practice in vehicle applications significantly support the investigation toward new applications in cooperative driving for road safety through communication.

All of the aforementioned applications of cooperative driving mainly focus on two issues: 1) the exchange of information among vehicles [24] and 2) the way the vehicles should be guided using the obtained information [25], [26]. The former issue is tackled through intervehicle communication, which extends the horizon of drivers by sharing information about driving status and intentions [13], [15], [27] [28] [29]–[32]). The latter issue is approached by using cooperative trajectory planning [13], [15], [27], [28], [33]–[36]. It should be noted that many new scenarios differentiate from the aforementioned methods by applying ad hoc networking [37]. These approaches integrate ad hoc connectivity, local peer-to-peer networking, and short-range communication [31]. However, intervehicle communication is still being researched due to varied driving behaviors and high mobility [31], whereas deploying and testing these networks also involve a high cost in the real world [38].

In this research context, the Integrated poject (IP) PReVENT took a first comprehensive step toward realizing the vision of a preventive and active safety zone around vehicles by means of complementary safety functions. This safety zone can be interpreted as a temporal dimension in terms of time to collision (or time to accident) as well as into a spatial dimension in terms of a 360° coverage and safety cushion around the vehicle. Importantly, safe speed and safe distance are key factors for safe driving. This is the reason why PReVENT defined a function field for this topic, within which the subproject wireless local danger warning (WILLWARN) contributed to foresighted driving by exploiting V2V communication.

WILLWARN started with the ambition to close the gap between former approaches like the simple "Extended Warning Flashlight" from the DEUFRAKO project intervehicle hazard warning [40] and the ad hoc network-based systems from the German project FleetNET [41] and the EU project CarTalk2000 [42], which presumed high equipment rates of vehicles. Thus, WILLWARN is a complete application that supports the driver in safe driving by applying intervehicle communication and enables an electronic safety horizon for foresighted driving.

The whole WILLWARN application is innovative with significant scientific and technological contributions summarized as follows:

1) a concept for automatic detection, localization, and relevance check of traffic and weather-based hazards through onboard sensors and a positioning system such as GPS;
2) a new warning message management for transmission, storage, and distribution of hazard warnings, ensuring driver information in time at the right spot;
3) a local self-organized car-to-car communication system for establishing a decentralized communication network with both oncoming and following cars;
4) a new approach for in-car message management and warning dissemination, decoupling the application functionality from the underlying communication technology. An application-based routing by store and forward in the application layer and ad hoc networking in the network layer was chosen.

It is also worth noting that in the framework of WILLWARN, an ad hoc wireless network simulation scheme that integrates all the crucial parameters for an accurate channel model characterization and performs in a computationally economic manner has been developed. The complexity and stochastic nature of the vehicular physical layer (PHY) communication environment (particularly in highway scenarios) made it necessary to develop a physical-layer simulation environment to provide estimations on both narrowband (propagation loss factor calculation) and wideband (multipath delay spread, structure of individual paths, channel's frequency selectivity) characteristics of the PHY wireless channel at frequencies around 5.9 GHz. The developed simulation environment has been set up based on the IEEE 802.11a orthogonal frequency-division-multiplexing transmission technology. The detailed description of the simulator features and respective simulation results in different environmental scenarios will be reported elsewhere.

The key feature of the WILLWARN application is the focus on low penetration levels in rural traffic [43] by a new message-management strategy; it is based on storing warning information in the vehicle and distributing warnings through communication, particularly with oncoming traffic. This leads to a high benefit for the user, even if the equipment rate is low.

First estimations assume that the system will already have a significant effect when 10% of the vehicles will be equipped [44]. At this point, it has to be mentioned that not only the equipment rate of vehicles will determine the effectiveness of cooperative systems. Fixed installed communication devices along the road [so-called roadside units (RSUs)] can also significantly contribute to the overall system performance. However, a detailed quantitative assessment of the system performance in different network densities is out of the scope of this paper. Currently, the WILLWARN system is explicitly evaluated in a large-scale field operational test in Germany (simTD), together with other applications [45], [46]. With over 400 vehicles and more than 100 RSUs, this field test shall exactly evaluate the performance of cooperative applications in different network densities and prepare corresponding strategies for market introduction.

All of the aforementioned modules and features of the proposed foresighted driving system are presented in this paper separately and in detail in the following sections.

II. System Overview

WILLWARN, in concept, is a decentralized information system that is based on an ad hoc (V2V) communication network. Vehicles automatically and without any driver intervention or action detect road hazards like, e.g., low road friction, and share this information with neighbored vehicles or vehicles, which come into radio range later on. This sharing of information enables drivers to adapt their driving style, therefore avoiding any hazards before they come into the drivers' visual range.

The WILLWARN system is based on a modular object-oriented architecture, as depicted in Fig. 1. It consists of the V2V communication module (VVC), the warning message-management module (WMM), the hazard-detection-management module (HDM), the hazard-warning-management module (HWM), a GPS receiver, and various onboard sensors.

The HDM module is connected to the vehicle's bus system through which onboard sensor data are collected and compared against specific sensor data patterns, according to which, hazards are detected. Once a potential hazard is detected, an "information package" describing the hazard is passed to the

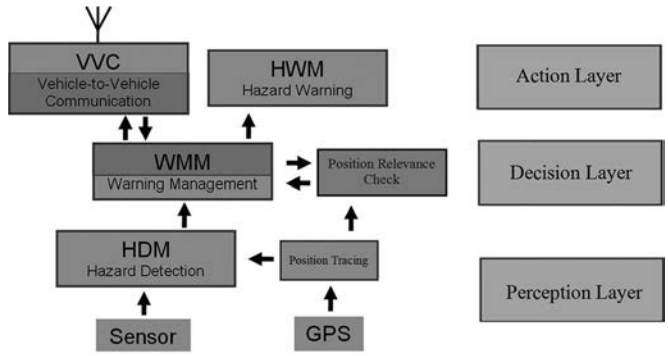

Fig. 1. WILLWARN system architecture.

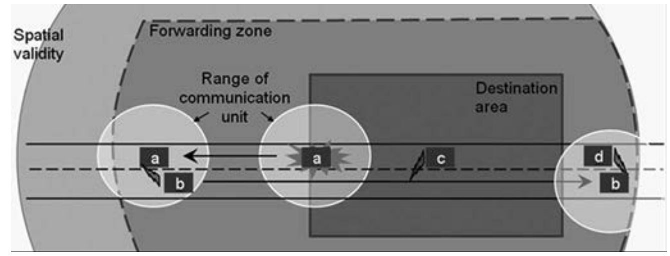

Fig. 2. Message distribution and related spatial definitions.

WMM module. It contains the type of the hazard, various data needed to describe the hazard, as well as other parameters. Such information includes the temporal validity of the hazard, an initial reliability value, a priority index, and an indication of the traffic direction (following, oncoming, or both) that can potentially be affected by the detected hazard. Analysis of the aforementioned parameters is given in the following section.

The WMM module performs the following: 1) processing of the "information package" sent by the HDM module; 2) processing of hazard messages received by the VVC module; 3) identification of hazard messages that need to be (re)sent by the VVC module; 4) recognition of any invalid or obsolete hazard messages (also considering the vehicle's current position, speed, and direction); and 5) preparation of the information data to be displayed to the vehicle's driver through the HWM module.

All hazard messages are communicated between neighbored vehicles, in ad hoc network architecture, through the VVC module. In addition, the latter applies geocasting algorithms and basic network layer functions for efficient multihops in dense network scenarios [47]. All of the received messages are also checked for plausibility based on the information available through the vehicle's own sensors. Accordingly, the received messages can also be negated. In addition, the received messages that are triggered by the same event are also combined to update the reliability of the received information. This is taken into account in the decision made by the WILLWARN module of whether to inform or not the driver about a specific hazard.

III. Parameters Affecting Message Distribution

A. Temporal Parameters

The temporal characteristics of hazard information primarily depend on hazard temporal validity and update cycle. Note that both of these parameters do not necessarily control the message distribution, but they are considered to achieve effective communication. Road hazards only exist for a certain time, e.g., an accident site is cleared after a while. In addition, hazard characteristics, such as the position of the end of a traffic jam or road friction coefficients, might significantly change over time. Thus, hazard information varies over time, meaning that neither the vehicle detecting the hazard nor the vehicles receiving the hazard message can accurately determine the hazard expiration time. Rather, hazard detection has to be guessed, considering the type of hazard and additional parameters relevant to the type of hazard.

A message is kept in the vehicle's database and distributed to neighbor vehicles as long as it is not expired. In addition, hazard messages may only be communicated to vehicles that may reach the described hazard before expiration time, meaning that, assuming a vehicle's maximum speed, the expiration time restricts and implicitly defines the area of distribution. On the other hand, a hazard may be detected by multiple vehicles, meaning that hazard information propagating within the network is updated with respect to time. Older information becomes obsolete. Nevertheless, some redundant messages are needed to increase and evaluate the reliability of the received hazard message.

The update cycle of a hazard message is determined by the frequency of equipped vehicles passing by the hazard location and the type of hazard, e.g., an accident will only be detected by the crashing vehicle; a jam end can be detected by all the vehicles entering the jam. The WMM module identifies messages describing the same hazard and chooses to combine the most recent ones based on the update time.

B. Spatial Parameters

By nature, information regarding the detected road hazards concerns multiple vehicles and large areas rather than to just a single dedicated neighbor vehicle. Within WILLWARN, the aforementioned area of interest is designated by three encapsulating areas, as depicted in Fig. 2. The largest area is designated as "spatial validity" area. It includes the region around the hazardous location in which the hazard (detected by vehicle (a); see Fig. 2) remains valid for traffic entering it. Note that the spatial validity area has been given a circular shape. Thereby, the architecture of the road network is not considered. Instead, the air line distance between neighbor vehicles (designated as (b)–(d) in Fig. 2) and the hazardous spot is considered (worst case). Additionally, the spatial validity area primarily depends on the hazard's temporal validity, meaning that it becomes smaller over time. The second largest area is designated as "forwarding zone." All vehicles within this area keep the hazard message in their database and "send queue" and communicate it to other neighboring vehicles as soon as they come into radio range. When the forwarding zone is left, the message is removed from the vehicle's database.

All vehicles moving toward the hazard spot and entering the destination area should receive the hazard message to ensure an appropriate timely warning. To reduce communication traffic, the destination area is set significantly smaller than the area defined by the spatial validity. This reduction can be achieved by heuristics regarding the relevant direction and the trace, e.g., some hazards are only relevant to vehicles driving in a defined direction. In addition, the destination area might be reduced for hazards having long temporal validity, e.g., it makes no sense to spread the information regarding black ice for several hundred kilometers, even if it might be assumed that the danger could remain valid for several hours during the night. Still the probability for vehicles far away from the hazard to actually end up at the location of the hazard is too small. Given this reduced destination area, there are vehicles that are outside the destination area during the first broadcast wave but reach the hazard location while the message is still valid. These vehicles have to be informed by repeating the message.

Moreover, it is essential for a hazard message to be communicated within the forwarding zone (in both traffic directions). Only in this way can it be ensured that the hazard messages are "physically" transported back to the destination area exploiting the oncoming traffic. Thus, it is important to also communicate messages to vehicles, which might not be affected by the corresponding hazard, e.g., to vehicles driving in the opposite direction on a motorway. These vehicles help to bridge the out-of-communicating gap between affected vehicles in a low equipment rate or a low-vehicle-density environment.

C. Supplementary Parameters

The WILLWARN system is designed to handle multiple hazard messages, each of which might concern different types of hazards. Thus, messages need to be prioritized based on the message content as follows: 1) imminent dangerous situations that require or may require immediate driver intervention; 2) situations that require particular driver attention but do not oppose imminent danger; and 3) additional traffic-related information where no particular driver attention is required. The priority parameter is used by the VVC module for prioritization of the messages if the "send queue" length or the communication capacity is exceeded. Additionally, the priority parameter is used by the WMM module if the space of the database is exceeded or if not all messages can be processed.

The critical parameter on the decision made by the WILLWARN module on whether to inform or not a driver about a specific hazardous event is the reliability parameter. This defines the probability of a hazard to be valid. A first indication in the reliability of an event (which is then transformed into a hazard message) is given by the HDM module based on the type of hazard, the applied sensors, and the sensor values. The reliability value is processed by the WMM module. Within the latter, the received messages that are triggered by the same event are also combined to update the reliability of the received information. The reliability of an event increases when messages describing the same event are received and decreases when contradictory messages are found. Note that the reliability of a message decreases over time where messages become invalid. Unreliable messages or obsolete messages are deleted from the vehicle's database and send queue.

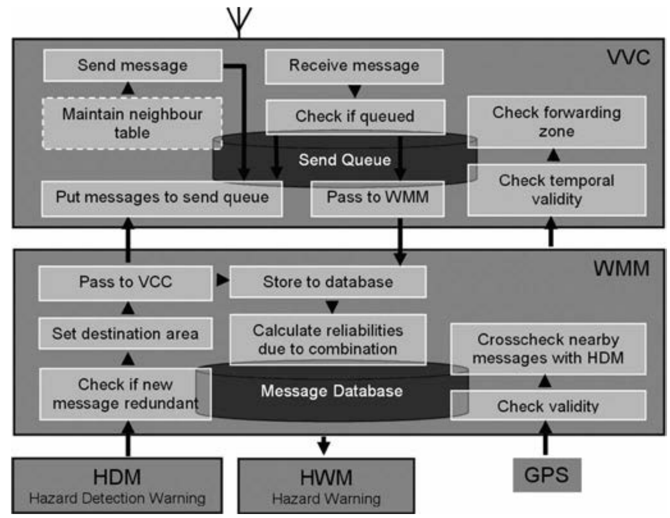

Fig. 3. Message distribution tasks within the WMM and VVC modules.

IV. Warning Message Management

In Fig. 3, an overview of the tasks necessary for hazard message management and distribution is depicted. As it can be seen from Fig. 3, all tasks are vertically divided into three groups. The left column consists of tasks dealing with sending of messages and generation of messages initiated by the HDM module. The tasks shown in the middle column are triggered by the reception of a new message. The tasks at the right column are periodically performed to keep the database up to date with respect to hazard message aging and vehicle's movement.

A. VVC Module Tasks

The VVC module has at least one "send queue." All of the hazard messages that need to be transmitted are initially stored in the "Send Queue." The latter consists of hazard messages passed to the VVC module by the WMM module, hazard messages received from other vehicles, and messages that have been transmitted and queued for retransmission. A received message is queued only when another message indicating the same event is not already queued. In addition, the received messages are put into different queues according to their priority values.

The VVC module uses a neighbour table to apply an adaptive and scalable L3 forwarding algorithm. This table contains information about communication partners in range, including their position. It is updated by frequent beaconing messages. WILLWARN messages are only sent when the neighbor table indicates that the other vehicles are in range. Note that the message repetition time is adapted based on the size of the neighbor table and the communication traffic, in general. Moreover, each message is passed only once to the WMM, unless it has been deleted from the "Send queue" in the meantime.

By using a geo-cast mechanism, the VVC module passes hazard messages to the WMM module, whereas the vehicle is in the received message's destination area. Since messages can be exchanged and forwarded between neighbor vehicles outside the message's destination area, the former can remain in VVC "Send queue" without the WMM module notifying them. These messages are passed to the WMM module later on when the vehicle enters the destination area.

To process the temporal validity, all vehicles need a synchronized clock as provided by GPS. Each message contains the timestamp and the time period indicating the temporal validity. Periodically, the temporal validity of all the messages in the "Send queue" is tested. Invalid messages are removed regardless if they have been communicated or not. Note that WILLWARN messages become spatial invalid before they become temporal invalid. However, spatial validity is not tested at the VVC module but at WMM module, which reports spatial invalid messages to the VVC module. Under normal conditions, all spatial invalid messages do not reach temporal invalidity. However, this parameter is needed given the fact that there are messages communicated outside the destination area that are not known to the WMM module and are therefore not checked for spatial validity.

As previously stated, the VVC provides distribution of a hazard message within the defined forwarding area. The latter is adapted according to the distribution algorithm. When the vehicle leaves the forwarding zone, the respective hazard message is deleted from the "Send queue." To do so, all of the messages in the "Send queue" are periodically checked.

B. WMM Module Tasks

As it can be seen from Fig. 3, part of the WMM module is the "Message Database." It consists of a series of clusters, each of which contains messages corresponding to a particular hazard event. A received message is added to a particular cluster based on the hazard type, hazard location, and relevance to the receiving vehicle's current position and direction. It should be noted that within a particular cluster, there might be messages indicating that a hazard event is no longer existent. Such "negative" messages have the same format like regular warning messages, and they are generated if the plausibility check for a received message is negative. Moreover, a cluster may contain messages with undefined reason.

As previously stated, a hazard reliability and relevance may change over time and space. Thus, a maintenance cycle is needed for each cluster to keep the hazard validity up to date. A maintenance cycle is triggered either periodically on position updates or after the reception of a relevant hazard message. Each hazard message contains a reliability value, whose initial value is given by the HDM module of the detecting vehicle. The latter depends on the hazard type and drops over time according to (1)

$$r_{\text{msg}}(t_{\text{now}}) = \frac{r_{\text{basic}}}{1 + 4\left(\frac{t_{\text{now}} - \text{mgt}}{t_{\text{exp}} - \text{mgt}}\right)^4} \tag{1}$$

where r_{msg} represents the message's current reliability, r_{basic} represents the hazard's initial reliability, t_{now} represents the current time, t_{exp} represents the message expiry time, and mgt is the message generation time. Note that (1) indicates that the message reliability slightly decreases during the first half of its temporal validity. At that point in time, the respective reliability is approximately 80% of the dedicated initial reliability. After that point of time, the reliability value decreases faster and is equal to 20% of its initial value when the message expiration time is reached.

The combined reliability of a message cluster is calculated from the single reliabilities of cluster messages. As a first step, the reliability values of positive and negative messages for which a reason k is explicitly defined are calculated [see (2)]. These values are then combined with the reliability values of positive and negative messages for which a reason is undefined, as depicted in (3)

$$r_{\text{cluster},k}(t) = \left(1 - \prod_{i=0} (1 - r_{\text{msg}+k,i}(t))\right) \cdot \prod_{j=0} (1 - r_{\text{msg}+k,i}(t)) \tag{2}$$

$$r_{\text{cluster}}(t) = \left(1 - \prod_{i=0} (1 - r_{\text{msg}+0,i}(t))\right) \cdot \left(\prod_{k=1} (1 - r_{\text{cluster},k}(t))\right) \cdot \left(\prod_{j=0} (1 - r_{\text{msg}-0,j}(t))\right). \tag{3}$$

At each maintenance cycle, the distribution relevance of every hazard message stored in the database is recalculated. This is used by the WMM module to give communication priority to the most relevant messages. In general, the distribution relevance R is calculated by summing up differently weighted relevance parameters f as follows:

$$R_{\text{msg}} = \frac{\sum_{i=1}^{I} c_i \cdot f_i}{\sum_{i=1}^{I} c_i} \tag{4}$$

where c_i's represent the weighting factors. Each hazard type is related to a predefined priority. Within WILLWARN, three priority categories are defined. Hazards that require the driver's immediate reaction to prevent an accident are assigned the highest priority. Hazards that require the driver's particular attention are assigned a medium priority. Finally, if a hazard message is only informative to the driver, then it is assigned the lowest priority. The relevance parameter f_P is calculated as follows:

$$f_P(\text{priority}) = \frac{\text{priority}}{\text{priority}_{\text{max}}}. \tag{5}$$

The relevance parameter corresponding to the distance between the vehicle and the hazard event is calculated by (6)

$$f_D(P_{\text{own}}, P_{\text{target}}) = \min\left(1, 0.5\frac{l_{\text{target}}}{|P_{\text{own}} - P_{\text{target}}|}\right) \tag{6}$$

where l_{target} is the length of the target area, P_{own} is the vehicle's own position, and P_{target} represents the position of the center of the target area. The relevance parameter considering the time elapsed since the last transmission of the considered hazard message is calculated as follows:

$$f_B(t_{\text{now}}, lst) = 1 - \frac{1}{1 + e^{(t_{\text{now}} - lst - 5s)}}. \tag{7}$$

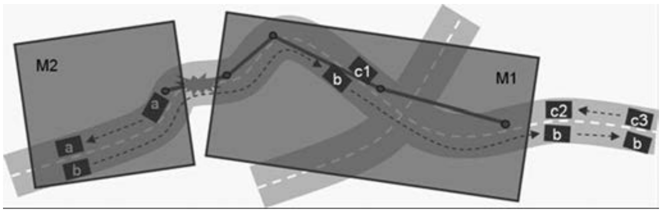

Fig. 4. Extending trace point chains of generated messages.

Accordingly, the distribution relevance R_{msg} is calculated by (8)

$$R_{\text{msg}} = \frac{2f_P + 1 \cdot f_D + 1 \cdot f_B + 1 \cdot r_{\text{msg}}}{2+1+1+1}. \quad (8)$$

After the combined reliability for a specific cluster exceeds the warning threshold, the local relevance of the hazard cluster is evaluated. Each message contains a set of coordinates that represents the path that leads to the hazard. The latter is used by the Positional Relevance Check submodule that attempts to match it to the vehicle's own trace points' chain. If none of the tracers can be matched, then the Positional Relevance Check submodule returns an invalid value, indicating to the WMM module that the message cluster is not locally relevant. It should be noted that only the positive messages of a cluster are used for trace point matching.

When the HDM sends a new "information package" to the WMM module, the latter scans the message database for stored messages describing the same hazard. In the case where the new information package does not significantly increase the reliability, the information from the HDM is discarded. The new information is discarded even if it is more up to date to avoid increasing the communication traffic due to weak update information. As long as the information is not discarded, several parameters necessary for message distribution, such as message expiration time (temporal validity), the forwarding zone, and the destination area, are defined. Together with the information package received by the HDM module, they are used to construct a new hazard message that is then stored in the "Message Database" either in an already-defined cluster or to a new cluster for further manipulation and later communication. On the other hand, when a new hazard message is received via the wireless interface, the WMM module checks its content for plausibility by applying the HDM module. If the described hazard event appears implausible, then a negative message is generated and stored in the corresponding message cluster instead of the received message. Otherwise, the received message is stored in the corresponding hazard cluster.

There are two cases in which the trace point chain of a generated message needs to be updated (see Fig. 4). The first case is when a hazard message is relevant to both traffic directions (following and oncoming). In this case, the detecting vehicle generates two messages for the same hazard event. The hazard message dedicated to the following traffic is assigned to the geographical area (as destination area) that is traveled by the detecting vehicle before reaching the hazardous spot and the vehicle's own trace points' chain. However, at the moment of detection, there is no respective information (destination area or trace points' chain) for the hazard message dedicated to the oncoming traffic. Thus, both the trace point chain and the destination area of that message are updated as the detecting vehicle drives upstream.

The second case for which the trace point chain needs to be updated is for moving hazards. This is mostly the case when the detecting vehicle itself is the hazard. An example for this is a slowly moving vehicle. Thus, as the detecting vehicle moves, the vehicle's trace point chain is constantly updated by the vehicle's last position.

V. Hazard-Detection Module

As described in Section II and depicted in Fig. 1, the system defines a functional chain for preventive safety applications in three phases, i.e., perception, decision, and action based on sensor information. The HDM is clearly a part of the perception layer and implements the automatic detection of road hazards. Since the detection of road hazards is conveyed from characteristic sensor patterns, the hazard detection module is connected to the vehicle's bus system.

A. *Principle of Hazard Detection*

The basic idea of hazard detection is to fuse the information available from various off-the-shelf onboard sensors to conclude on critical driving scenarios or critical environmental conditions. Detectable hazards have been identified in a matrix, where all sensors and related information have been listed. More precisely, this matrix links each hazard to the required information, which is available from different sensors. Following, based on the hazard matrix, the required input parameters for each single-detection algorithm can be determined. Moreover, a first classification with respect to the detection reliability can be made. Based on the hazard matrix in question, numerous hazards may be potentially detected through sensor data combination and fusion.

As mentioned in Section II, in the case where a hazard has been detected, the hazard-detection module provides the following information to the warning management: priority, temporal and spatial validity, relevant direction, and reliability. This information is used by the warning management for the further processing of the corresponding hazard message.

To avoid multiple detections related to the same hazard scenario, the single algorithms of the hazard-detection module need to implement some sort of hysteresis; for example, multiple detections related to reduced friction on a very short distance triggered by single electronic stability program (ESP) interventions describe the same hazardous spot. Therefore, only one of these detections should be considered by the hazard-detection algorithms.

To illustrate the functionality of the HDM, in the context of this paper, the detection of two hazards is in detail described in the following paragraphs: road obstacle and reduced friction.

1) Obstacle on the Road: This scenario exhibits the different levels of complexity that may be related to a single hazard type. An obstacle on the road may be, e.g., just a slow-moving or broken-down vehicle, but it might also be another (nonvehicular) object blocking the lane.

A slow-moving vehicle, e.g., a tractor, may just continuously transmit a corresponding warning message to the surrounding

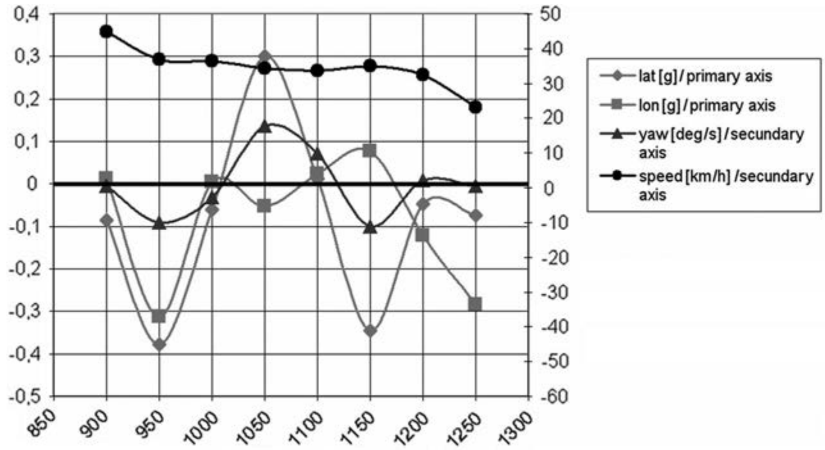

Fig. 5. Obstacle detection based on evasion maneuver.

vehicles. A broken-down vehicle by receiving information from its own onboard sensors related to warning flashing lights and speed value smaller than 5 km/h may also generate a corresponding warning message to following traffic. In case of another (nonvehicular) kind of obstacle, the latter may be detected by a vehicle, which performs an evasion maneuver to avoid the collision and transmits the warning message to the surrounding vehicles.

The detection of an obstacle based on an evasion maneuver is quite complex. However, several measurements prove that there is a characteristic correlated run of speed, lateral and longitudinal acceleration, and yaw rate. Moreover, the detection algorithm considers steering wheel speed. The basic approach is to continuously calculate a predicted driving path to identify an extraordinary but not anticipated maneuver, which probably indicates an obstacle on the road (see Fig. 5).

2) Reduced Friction: The detection of reduced friction is based on the single-lane one-wheel model of driving dynamics. The principle is described in [48] and [49]. Accordingly, the maximum of the μ values (friction coefficient) can be conveyed from the maximum lateral and longitudinal accelerations, which for simplification can be combined in the vehicles' center of gravity (see Fig. 6) as follows:

$$\mu_{\text{lateral}} = \frac{a_{\text{lateral}}}{g} \tag{9}$$

where μ is the friction coefficient, a_{lateral} is the lateral acceleration, and g is the acceleration due to local gravity.

While the single accelerations (longitudinal, lateral) can be measured by the corresponding sensors, the μ values can be calculated using [50] by (10)

$$\mu_{\text{lateral}} = 0.8 \cdot \mu_{\text{longitudinal}}. \tag{10}$$

This way, it is possible to continuously estimate the friction potential currently used by the vehicle. In case there is an intervention by ESP, anti-lock braking system (ABS), or acceleration skid control (ASR), it is clear that the maximal μ value has been reached. Therefore, an intervention by any of the mentioned assistant systems triggers the algorithm, which calculates an estimated friction value.

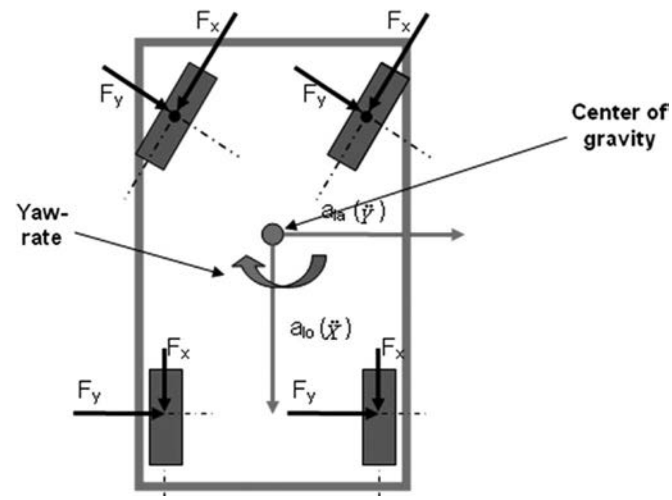

Fig. 6. Single-lane one-wheel model.

This algorithm has been extensively tested and validated in several driving tests [48]. Some tests have been carried out in northern Sweden to ensure defined constant testing conditions. It has been proved that the algorithm provides sufficient accuracy to estimate the friction potential of the road in a magnitude of four steps, which is more than sufficient for this application range.

Figs. 7 and 8 show the calculated friction value during a system intervention (ABS and ESP) on a dry road and on an ice plane. The gaps in the single graphs result from the fact that the friction potential has only been calculated in case of an intervention by the vehicles' assistance systems. The algorithms for the detection of obstacles on the road and reduced friction are protected by patent [49].

B. Plausibility Check of Received Hazard Information

The hazard-detection module not only performs the detection of hazards but also verifies the received hazard information. In this sense, the hazard-detection module checks the received information for plausibility and consistency. An important parameter for the verification of hazard information is the hazard reason, which is sent together with each hazard message. A receiving vehicle tries to confirm the hazard reason for the

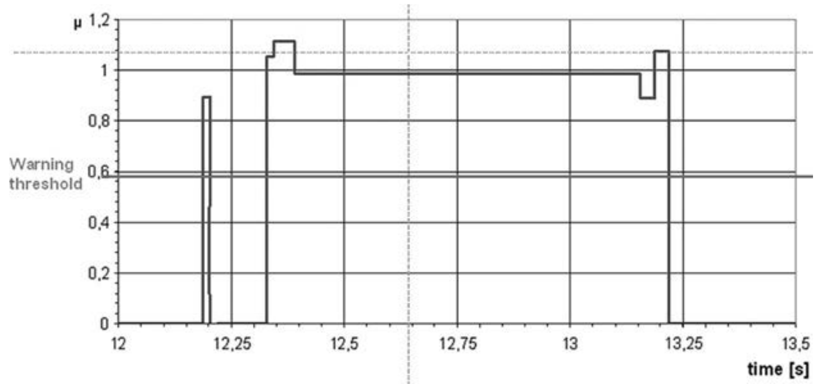

Fig. 7. Friction measurement. ESP intervention on a dry clean curve.

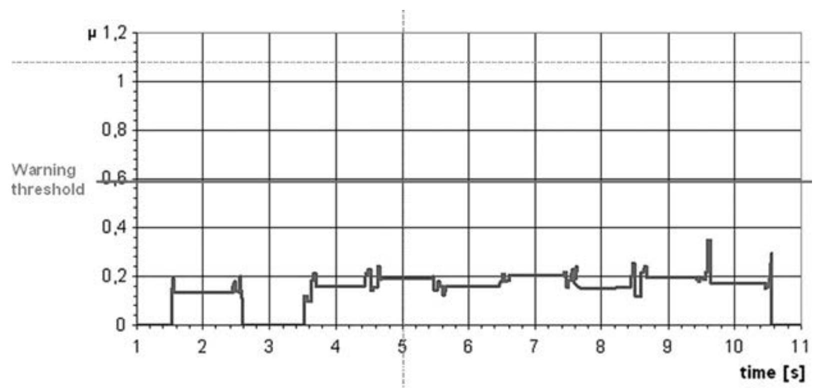

Fig. 8. Friction measurement. ABS intervention on a straight ice surface.

current position or the recently driven path. In this case, similar algorithms to those for hazard detection are applied. Again, a sensor pattern that corresponds to the received hazard information is evaluated. There are different scenarios for excluding the received hazard information. First of all, the hazard may be outdated. A simple example may be the stopped vehicle, which switches off warning flashing lights and continues moving on the road. Moreover, the received hazard information might be implausible. An example scenario would be the information about a traffic jam, but the receiving vehicle reaches and passes the hazardous area with high velocity.

In the case where the received hazard information has been identified as outdated or implausible, the hazard-detection module generates a warning message that negates the corresponding event. The information is passed to the warning-management module like a detected hazard, where an additional "negative" message is generated. As already described, these messages are distributed like common hazard messages and combined in the corresponding cluster. While usual hazard messages increase the reliability of the hazard event, "negative" messages decrease the reliability. Such negating messages are of great significance and importance for the superior reliability of the system.

VI. Positioning and Relevance Check

Positioning and relevance check basically fulfills three major tasks: First, it provides all residual modules with positioning and timing information. Second, it generates the trace point chains, which have to be added to each newly generated message ("Trace Point Casting"). Third, it matches its own current position to trace point chains to evaluate the local relevance of received messages ("Trace Point Chain Matching"). The corresponding algorithms will be explained in the following sections in more detail. Obviously, the prerequisite for these tasks is to have access to a positioning system like, e.g., GPS. Although additional map-based technology will surely simplify the applied algorithms, the system works with simple GPS only. As already mentioned in Section II, this is a very important requirement when the system will also be used in low-class vehicles. To increase the positioning accuracy, a differential GPS, like, e.g., European Geostationary Navigation Overlay Service, may be used with no effect on the WILLWARN system. High-class vehicles may additionally fuse the information from their onboard sensors, like, e.g., wheel speed, steering wheel angle, etc., to improve their positioning. However, improving the positioning accuracy does not effect how the single algorithms perform their tasks.

A. *Trace Point Casting*

As already described, each hazard message contains a so-called trace point chain (see Fig. 9), which describes the path leading to the hazard. A trace point chain consists of a set of eight GPS positions. The number of positions is limited due to the low bandwidth available in the vehicular-communication environment.

The receiving vehicles use the trace point chain to check the local relevance of a received message, which means that

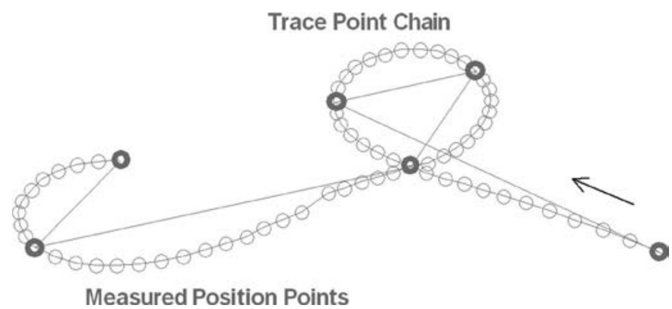

Fig. 9. Basic task of trace point casting.

it is verified whether the reported hazard is approached or not. Accordingly, each vehicle, which generates a warning message, must include a set of GPS locations that describe its positional history. The trace point chains of the existing messages must be completed stage wise, particularly when a warning message will be transmitted to oncoming traffic. While driving away from the hazard location, the transmitting vehicle just continuously adds a position to the trajectory until the chain consists of eight locations.

Usually, a standard GPS receiver provides position updates at 1 Hz. The simple alignment of the last eight positions for the trace point chain is not applicable. Detecting vehicles may move at different speeds. Moreover, the complexity of the road geometry leading toward the hazard is different for each scenario. Therefore, the trace point casting algorithm sorts out the GPS positions with low entropy to efficiently use the available bandwidth, e.g., a straight line only needs to be described with two positions. For all intermediate locations, the entropy would be zero. For a very curvy road, the situation is completely different. In this case, probably all GPS positions need to be considered to correctly describe the road geometry.

Therefore, the trace point casting algorithm only adds a new position to the trace point chain in case there is a significant change in the heading relative to its predecessor in the chain. Thereby, the speed of the vehicle is also considered. Moreover, there is a threshold for the maximum distance between two successive trace points in the chain. Otherwise, the distance between two trace points might become irrationally high in motorway scenarios, where a straight highway may be several kilometers long.

The choice of a relevant point is always realized starting from a comparison with the last significant casted point, according to a three-stage process.

1) The point must be at a distance of more than a minimum limit $s_{\min}$ from the last casted point. This avoids point accumulation when the vehicle is immobile or at low speed. If this condition is not satisfied, then the point is rejected; otherwise, the selection process continues.
2) The vehicle's heading angle change relative to the previous trace point must be higher than a minimum angle $\Delta\psi_{\min}$, and the weighted value with the traveled (or direct) distance must exceed the limit $\Delta\psi \cdot s \geq d_{\max}$. This criterion conditions the point selection where the vehicle turns. If these conditions are satisfied, then the point is casted; otherwise, the casting process continues to the third stage.

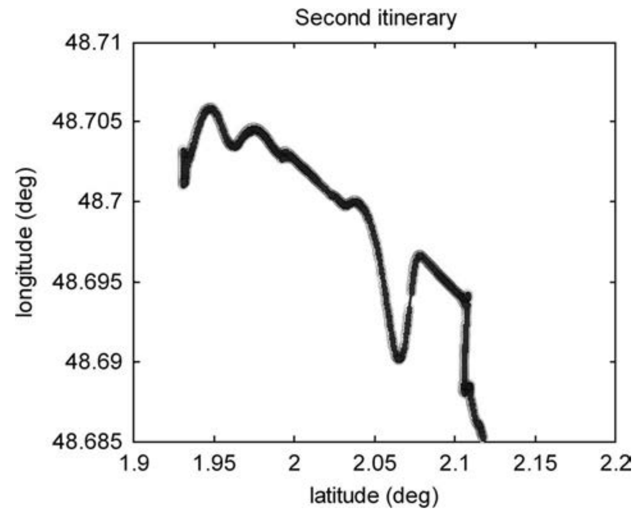

Fig. 10. Trace chains on a sample itinerary.

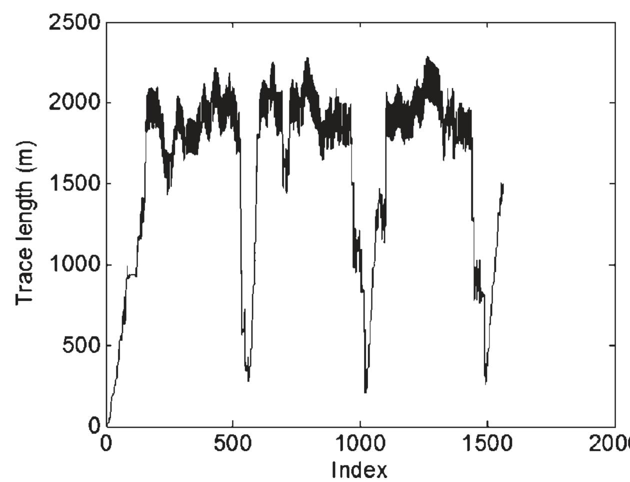

Fig. 11. Corresponding trace length.

3) When the previous conditions fail, the vehicle should be on a straight road section. If the traveled distance from the previous casted point is greater than a distance $s_{\max}$, then the point is casted. Otherwise, it is definitively rejected.

The choice of the four previous parameters ($s_{\min}, \Delta\psi_{\min}, d_{\max}, s_{\max}$) results from a compromise between accurate vehicle trajectory description and trajectory data compression. The selected values for these parameters are

$$s_{\min} = 20 \text{ m}, \qquad s_{\max} = 250 \text{ m}$$
$$d_{\max} = 60 \text{ m}, \quad \Delta\psi_{\min} = 15^\circ.$$

Thus, for eight significant points, the trace could measure between 160 m (most likely on urban roads) and 2 km (highway type). With these adjustments, the trace is quite representative in all of the trajectory cases followed by the vehicle.

Fig. 10 depicts the recorded trace chains on a sample two-lane highway type itinerary, whereas Fig. 11 represents the corresponding length.

The itinerary is first driven in one direction and then in the other direction (turn back on the left part). The practiced larger speed value is about 130 km/h on the straight section. In this case, the trace length is high; it decreases to about 300 m when the vehicle is in the high-curvature sections.

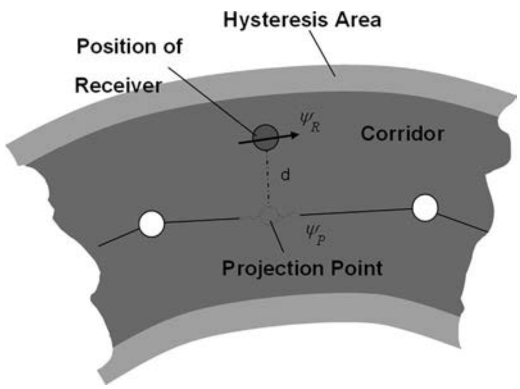

Fig. 12. Principle of trace point chain matching.

B. Trace Point Chain Matching

1) General Procedure: To verify the positional relevance of the reported hazards, each vehicle continuously evaluates the trace point chains of the received messages. More precisely, this algorithm tries to match its own current position to the trace point chains of the received messages. The task is rudimentary similar to a map-matching procedure. However, the algorithm for the trace point chain matching of the WILLWARN system is based on two fundamental mechanisms:

1) the comparison of its own current heading and the heading described by the trace point chain (verifying vehicle drives in the direction of the hazard);
2) the length of the perpendicular projection from its own current position on the trace point chain (distance of the verifying vehicle to the trace point chain).

In the case where the calculated distance between its own current position and the trace point chain is close to the threshold, a hysteresis prevents that the matching result toggles on different position updates (see Fig. 12).

2) Mathematical Description of Trace Point Chain Matching: To simplify the calculation, the single positions are transferred from spherical coordinates into flat coordinate values (x, y) as follows:

$$\begin{aligned} y &= \frac{\text{lat}}{360^\circ} * 2 * \pi * R \\ x &= \frac{\text{lon}}{360^\circ} * 2 * \pi * R * \cos\left(\frac{\text{lat}}{360^\circ} * 2 * \pi\right) \end{aligned} \tag{11}$$

where

lat latitude in degrees;
lon longitude in degrees;
R radius of the earth.

Consequently, the translated x values describe a position in west–east direction, and the translated y values represent a position in north–south direction. Naturally, this translation is just a simplification because it does not consider the earth's curvature. However, the error inherited by this simplification can be neglected since the distances between the involved positions are in the range of meters. Therefore, even the position height does not need to be considered.

After the conversion of the positions, the first step is to compare the heading of the verifying vehicle, which is obtained from GPS, to the direction implicitly given by the trace point chain. For this, the two successive positions of the trace point chain closest to the position of the verifying vehicle need to be identified. It is important to only consider successive points because the geometry of the path described by the trace point chain is related to the order of the single positions. The distance between the vehicle's position and the single trace points is simply calculated by (12)

$$|\vec{p}_{\text{currentPos}}(x, y) - \vec{p}_{i,\text{tracePointChain}}(x, y)| \,. \tag{12}$$

The two successive points closest to the position of the verifying vehicle describe a straight line according to (13)

$$\begin{aligned} P(x, y) &= \vec{p}_1 + \lambda(\vec{p}_2 - \vec{p}_1) \\ P(x, y) &= \vec{p}_1 + \lambda\vec{d} \end{aligned} \tag{13}$$

where p_1 and p_2 are two successive trace points, d represents the direction, which is implicitly given by the two selected points of the trace point chain, and λ is a scalar that determines any point on the straight line described by (13).

The heading of the verifying vehicle is obtained from GPS and usually represented in degrees relative to north. To compare the direction of the vehicle to the direction of the trace point chain, the direction vector of (13) is also converted in degrees relative to north as follows

$$\alpha = \arctan\left(\frac{d_y}{d_x}\right) \tag{14}$$

where d_y represents the amount of direction vector in north–south direction, and d_x represents the amount of direction vector in east–west direction. To obtain the absolute direction relative to north (β), the following cases have to be differentiated:

$$\begin{aligned} d_x > 0; d_y > 0: &\quad \beta = \frac{\pi}{2} - \alpha \\ d_x > 0; d_y < 0: &\quad \beta = \frac{\pi}{2} + \alpha \\ d_x < 0; d_y < 0: &\quad \beta = \frac{3}{2}\pi - \alpha \\ d_x < 0; d_y > 0: &\quad \beta = \frac{3}{2}\pi + \alpha. \end{aligned}$$

In the case where the deviation between the two headings is below a certain threshold, then the distance between the position of the verifying vehicle and the trace point chain (perpendicular projection on the trace point chain) is calculated by (15)

$$\begin{aligned} \lambda_{\text{lot}} &= \frac{d_x \cdot \text{currentPos}_x + d_y \cdot \text{currentPos}_y - d_x \cdot p_{1x} - d_y \cdot p_{1y}}{d_x^2 + d_y^2} \\ \vec{p}_{\text{lot}} &= \vec{p}_1 + \lambda_{\text{lot}}\vec{d} \\ \text{distance} &= |\vec{p}_{\text{lot}} - \vec{p}_{\text{currentPosition}}| \end{aligned} \tag{15}$$

where

currentPos_x x coordinate of the verifying vehicle;
currentPos_y y coordinate of the verifying vehicle;

$P1_x$	x coordinate of the first trace point (base point of the linear equation/straight line);
$P1_y$	y coordinate of the first trace point (base point of the linear equation/straight line);
λ_{lot}	value of λ that describes the point where the perpendicular projection crosses the straight line (projection point);
P_{lot}	projection point.

In the case where the distance is below a defined threshold and the criterion $0 \leq \lambda_{\mathrm{lot}} \leq 1$ is fulfilled, the algorithm has identified a match.

3) Evaluation of Trace Point Chain Matching Algorithm: The algorithm has extensively been tested with position data of many measurement drives. The measurements include the most critical scenarios for matching algorithms: motorway junctions, parallel roads, intersection scenarios, roundabouts, etc. Moreover, the test data included several long-term measurements (usual drives), including motorway and rural sections. In all the described scenarios, the algorithm proved its value with correct decisions between 96% and 100%, except in the case of multilevel crossing or parallel road, where the algorithm performance depends on GPS data accuracy [48].

VII. Communication Equipment

The right decision on the most suitable communication system is critical for the success of the WILLWARN application. The communication system needs to support WILLWARN application at a low cost and still be shared by other applications. Practical implementation requires that only local communication is considered, thereby excluding the vast research area of mobile IP, Internet gateways on the road, etc. Still, RSUs are included; however, their backbone connection is out of scope.

IEEE802.11p is likely to become the wireless standard for V2V and V2I communication in the United States due to its benefits in terms of hardware costs, bandwidth, latency, reliability, and communication range. Recently, in Europe, a European Control Conference decision has been made on the harmonized used of the 5875–5905 MHz band on a nonexclusive basis for intelligent transportation system road safety applications. Thus, it is very likely that a similar system, based on the same protocol (802.11p), adapted to European requirements, will become the European standard for V2V communication [52]–[54]. Due to 802.11p technological advantages, on one hand, and the likelihood of being deployed in the United States and adapted by the Car-to-Car Communication consortium (C2C-CC) on the other hand, the WILLWARN consortium decided to focus on the IEEE 802.11a-based communication systems due to the latter market availability and similarity to 802.11p [53], [54] protocol in terms of modulation scheme and frequency allocation. The latter has also been used as a V2V communication interface for system demonstration and integration testing.

VIII. Hazard Warning Management

A well-designed human–machine interface (HMI) is important for the driver to gain trust in the system. However, warning a driver, both reliably and on time, of a potential hazard that is not at the driver's line of sight is not an easy task.

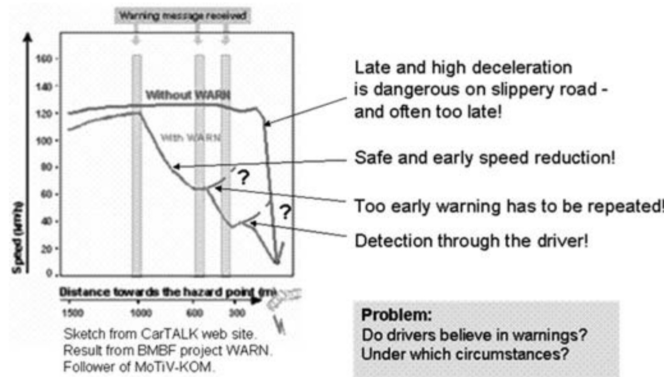

Fig. 13. HMI aspects.

A too early warning may result in the driver forgetting it or even ignoring it. On the other hand, repeated warnings regarding the same hazard might annoy the driver. In addition, a warning system that produces a large amount of warnings may lose its importance for the driver, resulting in an inappropriate driver's reaction. The problem of early and repeated warnings is depicted in Fig. 13.

Critical to the success of the WILLWARN system is achieving trust from the driver and keeping it in high levels, although hazard detection is sometimes based on "fuzzy" information, which can result in false alarms. Detection of low friction through ABS, ESP, or ASR means that the detecting vehicle is reaching its dynamical limits. However, each vehicle's dynamical limits depend, aside from the vehicle's speed, both on the vehicle's type and the condition of the vehicle's tires. Thus, low-friction conditions to one vehicle do not necessarily mean similar conditions to another vehicle that is supported by less worn-out tires or more advanced driving-assistance systems. This means that a low friction hazard could be classified to "actual danger" in the case where it is detected through driving dynamic assistance systems and to "potential danger" in the case where a friction reduction is deduced from wipers and/or rain sensors.

On the other hand, obstacles, which are moving or stationary (humans, animals, objects, etc.), can, most times, be considered as a potential danger, due to the formers' dynamic nature, in terms of position uncertainty. In addition, there is the problem of different hazards resulting in the same sensor patterns, which is often met on low-cost vehicles that are equipped with a limited number and non-state-of-the art sensors. In this case, it is difficult to differentiate the respective hazards resulting in an uncertainty to the displayed warning information.

Since early warning based on sometimes fuzzy information is a new approach to foresighted driving, only some specific guidelines have been worked out. In addition, some preliminary driving recommendations regarding speed and distance have been worked out, and relevant parameters or actions were defined such as warning timing, mode, intensity, sequence, repetition time, and hazard content. Warnings within the WILLWARN system are classified as "actual danger" and "potential danger" based on the hazard detection reliability or the

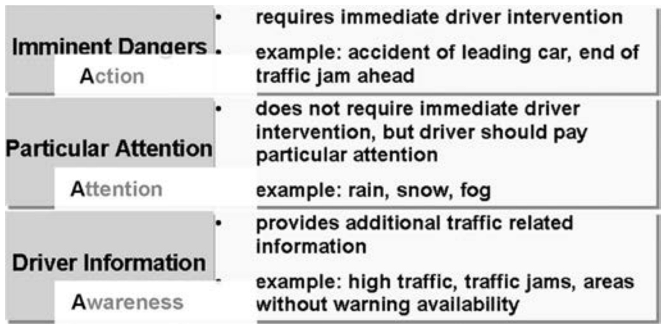

Fig. 14. Different grades of required driver action based on danger classification.

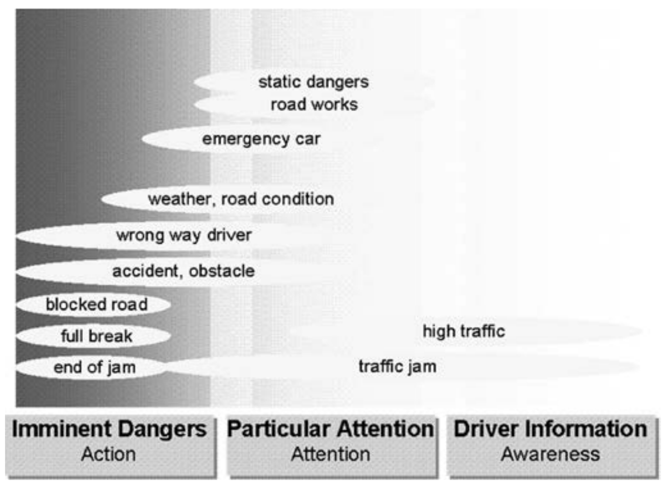

Fig. 15. Classification of hazards.

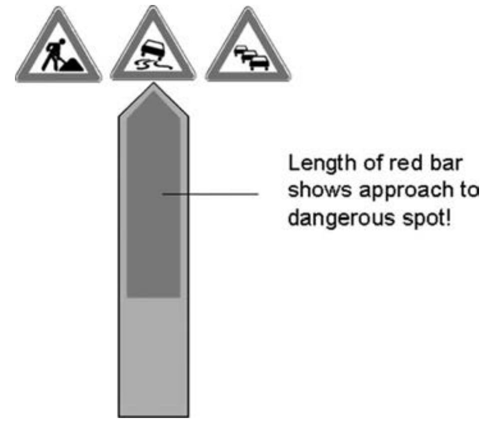

Fig. 16. WILLWARN system graphical display.

Fig. 17. Map representation of a warning.

time difference between hazard detection and warning message reception or warning message display on the receiving vehicle. This classification helps overcoming hazard uncertainty and still keeps trust of drivers to the systems on high level. In addition, a hazard warning is suppressed or intensified in the receiving vehicle according to the vehicle's speed. The applied classification is depicted in Fig. 14.

A warning of the class "actual danger" addresses an imminent danger that requires from the immediate action of the driver, such as a braking maneuver. On the other hand, a "potential danger" requires the driver's particular attention and adaptation of speed and distance. In addition to the aforementioned general classification, an additional class can be the "foresighted information" that increases the awareness of the driver.

In Fig. 15, the classification of dangerous situations according to the previously described required driver actions is depicted.

Obstacles are considered an "actual danger" only in the case where the time difference between detection and warning reception and display is below a certain threshold. Otherwise, a "potential danger" is reported since obstacles might have been moved or removed from the road. In addition, hazards that are difficult to be differentiated by the HDM module, such as snow, rain, and ice, are communicated to the driver as the same general hazard type that represents them all such as "reduced friction." However, an indication of the cause of the hazard is provided to the driver based on the type of hazard and received message reliability.

In addition, the developed HMI provides information, when feasible, regarding the distance between the dangerous spot and the receiving vehicle current position. A graphical display, similar to that used in navigation systems, has been applied, in which there is an indication of the relative distance via the length of a bar graph and the icon of the danger ahead. In Fig. 16, a snapshot of the implemented design is depicted. It should be noted, however, that both acoustic and optical display of a warning, when possible, is provided to the driver. The WILLWARN system may also use the map display of a navigation system, if the latter is available, to specify to the driver the exact position of a dangerous spot, as depicted in Fig. 17.

Finally, it should be noted that prior to informing the driver about a reliable and relevant hazard, the situational relevance is performed by the HWM module. The latter is directly related to the hazard type itself. One example is a scenario where the vehicle actually approaches a hazard location but its speed is already significantly low. In this case, a warning might be needless.

IX. Discussion and Conclusion

WILLWARN supports the driver in safe driving by intervehicle communication and enables an electronic safety horizon for foresighted driving.

The main features of the proposed system as described in detail in the previous sections are as follows:

1) onboard hazard detection based on data from the vehicle buses (e.g., obstacles, reduced visibility, bad road conditions, construction sites);
2) in-car warning management for low-equipment-rate application-based routing;
3) decentralized distribution of warnings and incident messages from store and forward to ad hoc car-to-car communication;
4) position-based relevance check by comparison of vehicle position and the position trace leading to the hazardous area;
5) timely driver warning by a graphical display and warning sound signals only if the driver is on the dangerous path.

The significant scientific and technological contributions of WILLWARN are mainly the automatic hazard detection, the position-based relevance check, and the application-based routing and information dissemination in vehicular ad hoc networks.

The system characteristics enable an inexpensive approach, which can easily be integrated to vehicles of all price ranges. WILLWARN requires access to in-vehicle bus systems, in particular CAN, to gather vehicle data from onboard sensor systems. A GPS antenna is used for position detection. WILLWARN uses available low-cost communication equipment off the shelf in a frequency band close to 5.9 GHz that has recently been allocated in Europe.

A suitable description of interfaces (HW/SW) and the modular design of the system enabled a successful implementation of the WILLWARN function in different cars and on different computers with different operating systems. Six demonstrator cars were built, two RSUs were developed, and all parts and subsystems were successfully validated.

Hazard detection algorithms, particularly for friction detection, proved their expected performance in many experiments and tests on ice and snow. It was shown that reduced friction can be detected, which are enough for the WILLWARN application.

Position detection by GPS and position relevance check by comparing its own position with the received critical path (trace point chain) have successfully been tested on all types of roads, even in complicated topological situations. The tests showed that the GPS quality is sufficient for position detection.

The communication hardware, which was used for WILLWARN, was bought off the shelf, and antennas and cable length were not optimized. However, static and dynamic range measurements proved that a range between 350 and 500 m is achievable. Full function test demonstrations showed that this is adequate for the WILLWARN function.

Full system tests were carried out to evaluate the performance of warning dissemination in a vehicle network. The final demo showed proper operation of the entire system.

Moreover, acceptance studies based on questionnaires and a drive simulator experiment verified the WILLWARN concept: Early hazard warnings lead to early speed reduction and a safe approach to the dangerous spot.

WILLWARN performs equally well on rural road and highway scenarios, where the tackled accident scenarios mostly happen. The system enables a high benefit for the driver, even at low equipment rates, because warnings are stored and physically transported in the cars when the equipment rates or the traffic is low. Oncoming traffic is also used for warning dissemination.

WILLWARN can be combined with existing infrastructure information from radio data system/traffic message channel, where some hazard warnings are already available. This improves the introduction phase, where only a few vehicles equipped with communication are on the road. However, the warning and incident information generated and provided by WILLWARN have higher timeliness, reliability, and far better localization than currently available information systems.

Importantly, the algorithms and protocols developed in WILLWARN are independent of the frequency band that is actually used and the communication standard. This guarantees that WILLWARN can be realized with other communication hardware in this emerging and fast-developing technology field.

Cooperative driving is currently an active area of research, where considerable effort is put on providing drivers with precise information about their surrounding and actions of others to have a valuable decision support system.

WILLWARN has contributed a lot of valuable results to the research of communication-based early warning and could be one of the starting applications for vehicle communication—and this will lead to safer driving.

The next generation of systems should be based on microcontrollers or at least on Car-PCs. HMI and driver behavior should be investigated further. Optimal timing for early warnings is necessary for customer acceptance.

Other behavioral effects like risk compensation have to be studied. PReVENT WILLWARN showed that communication is the next step and the right way to improve traffic safety in the future.

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References

[1] L. Giubbolini, "A multistatic microwave radar sensor for short range anticollision warning," *IEEE Trans. Veh. Technol.*, vol. 49, no. 6, pp. 2270–2275, Nov. 2000.

[2] T. Kato, Y. Ninomiya, and I. Masaki, "An obstacle detection method by fusion of radar and motion stereo," *IEEE Trans. Intell. Transp. Syst.*, vol. 3, no. 3, pp. 182–188, Sep. 2002.

[3] R. Kuc and B. Barshan, "Navigating vehicles through an unstructured environment with sonar," in *Proc. IEEE Int. Conf. Robot. Autom.*, Scottsdale, AZ, 1989, pp. 1422–1426.

[4] S. Atev, H. Arumugam, O. Masoud, R. Janardan, and N. P. Papanikolopoulos, "A vision-based approach to collision prediction at traffic intersections," *IEEE Trans. Intell. Transp. Syst.*, vol. 6, no. 4, pp. 416–423, Dec. 2005.
[5] A. Steinfeld, D. Duggins, J. Gowdy, J. Kozar, R. MacLachlan, C. Mertz, A. Suppe, C. Thorpe, and W. Chieh-Chih, "Development of the side component of the transit integrated collision warning system," in *Proc. 7th Int. IEEE Conf. Intell. Transp. Syst.*, Oct. 2004, pp. 343–348.
[6] W. R. Swihart and J. D. Woll, "Integrated collision warning and vehicle information systems for heavy vehicles," in *Proc. IEE Colloq. Monitoring Driver Vehicle Performance*, London, U.K., 1997, pp. 2/1–2/7.
[7] J. D. Woll, "Radar-based adaptive cruise control for truck applications," presented at the Soc. Automotive Eng. Int. Truck Bus Meeting Exhib., Cleveland, OH, 1997, SAE Paper 973 184.
[8] H.-S. Tan and J. Huang, "DGPS-based vehicle-to-vehicle cooperative collision warning: Engineering feasibility viewpoints," *IEEE Trans. Intell. Transp. Syst.*, vol. 7, no. 4, pp. 415–428, Dec. 2006.
[9] M. Kais, L. Bouraoui, S. Morin, A. Porterie, and M. Parent, "A collaborative perception framework for intelligent transportation systems applications," in *Proc. World Congr. Intell. Transp. Syst.*, Nov. 2005.
[10] J. Luo and J.-P. Hubaux, "A survey of inter-vehicle communication," School Comput. Commun. Sci., Swiss Fed. Inst. Technol., Lausanne, Switzerland, 2004.
[11] Y. Shiraki, T. Ohyama, S. Nakabayashi, and K. Tokuda, "Development of an inter-vehicle communications system," *OKI Tech. Rev. 187*, vol. 68, pp. 11–13, 2001.
[12] P. Varaiya, "Smart cars on smart roads: Problems of control," *IEEE Trans. Autom. Control*, vol. 38, no. 2, pp. 195–207, Feb. 1993.
[13] S. Kato, S. Tsugawa, K. Tokuda, T. Matsui, and H. Fujii, "Vehicle control algorithms for cooperative driving with automated vehicles and intervehicle communications," *IEEE Trans. Intell. Transp. Syst.*, vol. 3, no. 3, pp. 155–160, Sep. 2002.
[14] S. Tsugawa, S. Kato, K. Tokuda, T. Matsui, and H. Fujii, "A cooperative driving system with automated vehicles and inter-vehicle communications in Demo 2000," in *Proc. IEEE Conf. Intell. Transp. Syst.*, Oakland, CA, 2000, pp. 918–923.
[15] A. R. Girard, J. B. de Sousa, J. A. Misener, and J. K. Hedrick, "A control architecture for integrated cooperative cruise control and collision warning systems," in *Proc. 40th IEEE Conf. Decision Control*, Orlando, FL, 2001, pp. 1491–1496.
[16] Y. Yamamura and Y. Seto, "A design method for string-stable ACC using vehicle-to-vehicle communication," presented at the 12th ITS World Congr., San Francisco, CA, 2005, Paper 20058997.
[17] P. Mathias, "The intelligent cooperative intersection as part of urban traffic control systems," presented at the 12th Intell. Transp. Syst., World Congr., San Francisco, CA, 2005.
[18] S. E. Shladover, "Effects of traffic density on communication requirements for cooperative intersection collision avoidance systems (CICAS)," presented at the 12th ITS World Congr., San Francisco, CA, 2005.
[19] M. Tamura, S. Takahashi, S. Yasuhara, M. Kojima, and K. Minegishi, "Development of intersection safety support systems using vehicle-to-vehicle communication," presented at the 12th Intell. Transp. Syst., World Congr., San Francisco, CA, 2005.
[20] R. Miller and H. Qingfeng, "An adaptive peer-to-peer collision warning system," in *Proc. IEEE 55th Veh. Technol. Conf.*, Birmingham, AL, 2002, pp. 317–321.
[21] X. Yang, L. Liu, H. Vaidya, and F. Zhao, "A vehicle-to-vehicle communication protocol for cooperative collision warning," in *Proc. 1st Annu. Int. Conf. Mobile Ubiquitous Syst.: Netw. Services*, 2004, pp. 114–123.
[22] R. Sengupta, S. Rezaei, S. Shladover, D. Cody, S. Dickey, and H. Krishnan, "Cooperative collision warning systems: Concept definition and experimental implementation," *J. Intell. Trans. Syst.*, vol. 11, no. 3, pp. 143–155, Jul. 2007.
[23] M. Nakamura, H. Kawashima, T. Yoshikai, and K. Aoki, "Road-vehicle cooperation driving system," in *Proc. Vehicle Navigation Inf. Syst. Conf.*, Yokohama, Japan, 1994, pp. 425–430.
[24] L. Wischhof, A. Ebner, and H. Rohling, "Information dissemination in self-organizing intervehicle networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 6, no. 1, pp. 90–101, Mar. 2005.
[25] L. Li and F.-Y. Wang, "Cooperative driving at blind crossings using intervehicle communication," *IEEE Trans. Veh. Technol.*, vol. 55, no. 6, pp. 1712–1724, Nov. 2006.
[26] J. Huang and H.-S. Tan, "Error analysis and performance evaluation of a future-trajectory-based cooperative collision warning system," *IEEE Trans. Intell. Transp. Syst.*, vol. 10, no. 1, pp. 175–180, Mar. 2009.
[27] J. K. Hedrick, M. Tomizuka, and P. Varaiya, "Control issues in automated highway systems," *IEEE Control Syst. Mag.*, vol. 14, no. 6, pp. 21–32, Dec. 1994.
[28] O. Gehring and H. Fritz, "Practical results of a longitudinal control concept for truck platooning with vehicle to vehicle communications," in *Proc. IEEE Conf. Intell. Transp. Syst.*, 1997, pp. 117–122.
[29] A. M. K. Cheng and K. Rajan, "A digital map/GPS based routing and addressing scheme for wireless ad-hoc networks," in *Proc. IEEE Intell. Veh. Symp.*, 2003, pp. 17–20.
[30] J.-P. Hubaux, S. Capkun, and J. Luo, "The security and privacy of smart vehicles," *IEEE Security Privacy*, vol. 2, no. 3, pp. 49–55, May/Jun. 2004.
[31] L. Chisalita and N. Shahmehri, "A peer-to-peer approach to vehicular communication for the support of traffic safety applications," in *Proc. IEEE Int. Conf. Intell. Transp. Syst.*, 2002, pp. 336–341.
[32] J. Blum, A. Eskandarian, and L. J. Hoffman, "Performance characteristics of inter-vehicle ad hoc networks," in *Proc. IEEE Conf. Intell. Transp. Syst.*, 2003, vol. 1, pp. 114–119.
[33] Y. Chang and K. Kurami, "Longitudinal guidance and control for the entry of vehicles onto automated highways," in *Proc. IEEE Conf. Decision Control*, 1993, vol. 2, pp. 1891–1896.
[34] P. Kachroo and Z. Li, "Vehicle merging control design for an automated highway system," in *Proc. IEEE Conf. Intell. Transp. Syst.*, 1997, pp. 224–229.
[35] J. W. Choi, T. H. Fang, S. Kwong, and Y. H. Kim, "Remote-controlled platoon merging via coder–estimator sequence algorithm for a communication network," *IEEE Trans. Ind. Electron.*, vol. 50, no. 1, pp. 30–36, Feb. 2003.
[36] S. Joo, X. Y. Lu, and J. K. Hedrick, "Longitudinal maneuver design in coordination layer for automated highway system," in *Proc. Amer. Control Conf.*, 2003, vol. 1, pp. 42–47.
[37] J. J. Blum, A. Eskandarian, and L. J. Hoffman, "Challenges of intervehicle ad hoc networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 5, no. 4, pp. 347–351, Dec. 2004.
[38] F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "CityMob: A mobility model pattern generator for VANETs," in *Proc. IEEE Conf. Commun. Workshops*, 2008, pp. 370–374.
[39] [Online]. Available: http://www.prevent-ip.org/
[40] M. Chevreuil, "IVHW: An inter-vehicle hazard warning system concept within the DEUFRAKO program," presented at the e-Safety, Lyon, France, Sep. 16–18, 2002, Paper No. 2016.
[41] FleetNet—Internet on the Road, 2003. [Online]. Available: www.fleetnet.de
[42] European Project contract-number IST-2000-28 185 CarTalk. [Online]. Available: www.cartalEOOO.net
[43] S. E. Shladover, G. Polatkan, R. Sengupta, J. VanderWerf, M. Ergen, and B. Bougler, "Dependence of cooperative vehicle system performance on market penetration," *Trans. Res. Rec.: J. Trans. Res. Board*, vol. 2000, pp. 121–127, 2007.
[44] M. Schulze, G. Noecker, and K. Boehm, "PReVENT: A European program to improve active safety," in *Proc. 5th Int. Conf. Intell. Trans. Syst. Telecommun.*, Brest, France, Jun. 27–29, 2005.
[45] simTD—Sichere Intelligente Mobilität Testfeld Deutschland (Safe Intelligent Mobility Test Area Germany). [Online]. Available: http://www.simtd.de
[46] M. Fünfrocken, B. Allani, T. Baum, A. Hinsberger, J. Vogt, S. Weber, and H. Wieker, "Management of roadside units for the simTD field test (Germany)," in *Proc. 16th World Congr. Intell. Trans. Syst.*, Stockholm, Sweden, 2009.
[47] A. Hinsberger, "Dissemination of hazard messages in vehicular ad-hoc networks," presented at the World Congr. Intell. Transp. Syst., London, U.K., 2006. [Online]. Available: Paper ID 1356
[48] [Online]. Available: http://www.prevent-ip.org/en/prevent_subprojects/_safe_speed_and_safe_following/willwarn/
[49] FORGIS—Institute of Vehicle Technology and Environmental Technology, Friction and Obstacle Detection, 2005. [Online]. Available: http://www.forgis.de/deutsch/friction_obstacle_detection.pdf
[50] I. Weber, "Verbesserungspotenzial von Stabilisierungssystemen im Pkw durch eine Reibwertsensorik," Ph.D. dissertation, Tech. Univ. Darmstadt, Darmstadt, Germany, 2004.
[51] Network on Wheels (NoW). [Online]. Available: http://www.network-on-wheels.de/
[52] Car-to-Car Communication Consortium (C2C-CC). [Online]. Available: http://www.car-2-car.org/
[53] [Online]. Available: http://standards.ieee.org/getieee802/802.11.html
[54] [Online]. Available: http://ieee802.org/11/