Connected Cruise Control
Final report

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Delft, 26th March 2013

Preface

This report describes the final results of the Connected Cruise Control project. The Connected Cruise Control project was conducted from December 2009-April 2013 as a High Tech Automotive System Innovation project (HTASD09002), subsidized by Agentschap NL. The project was conducted by a consortium consisting of Clifford, Delft University of Technology, Eindhoven University of Technology, NAVTEQ/NOKIA, NXP, Rijkswaterstaat, SAM, SWOV, Technolution, TNO and the University of Twente. Delft University of Technology was prime contractor and leader of the consortium.

Many thanks to all contributors to the project!

Prof Dr Bart van Arem
Project manager Connected Cruise Control

Delft, 26th March 2013

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1. Three reasons for Connected Cruise Control

Mobility is one of the pillars of the Dutch economy and society. Mobility is under pressure by congestion in the Netherlands and other densely populated areas. In its focus area Driving Guidance, the HTAS Innovation program formulated the ambition to come to a 25% reduction in travel delay time (HTAS, 2009). Initially, the HTAS Driving Guidance program focused on the on board technology of a vehicle. In order to take further steps to combat congestion it is essential to ‘connect’ to the road-side infrastructure and use additional information and tools that are outside the vehicle.

Traffic efficiency

High expectations rest on so-called Advanced Driver Assistance Systems (ADAS) and In-vehicle information systems (IVIS) to reduce congestion. ADAS support or take over the operational driving task. IVIS support the strategic driving task by providing information on traffic flow conditions in the network. ADAS and IVIS are products primarily intended to improve the comfort, efficiency and safety of driving. Nevertheless, they can also contribute to societal objectives such as the reduction of congestion. Simulation studies have shown that a full range Adaptive Cruise Control can lead to 30% delay reduction in a congestion situation at a lane drop scenario if only 10% of the vehicles is equipped (Van Driel & van Arem, 2010). Experimental studies on IVIS show a delay reduction of 10-20%, especially in the case of non-recurrent traffic conditions due to road works and incidents (Lee & Park, 2008).

The missing link

ADAS systems such as Adaptive Cruise Control support operational driving tasks and IVIS systems such as Navigation with Real time traffic information support strategic driving tasks. There is a lack of systems that support tactical driving tasks such as speed, headway and lane choice. Connected Cruise Control (CCC) is a breakthrough application in this direction. It provides an advice to the driver regarding speed, headway and lane in order to anticipate to and eventually prevent congestion. It is based on the integration of in-vehicle systems and road-side algorithms for traffic flow improvement. As a first step it can be introduced as a retrofit nomadic device. In this way it can rapidly gain a substantial penetration rate and provide a foundation for OEM fitted systems with active vehicle control.

The automotive telematics market

Growing demand for personal device connectivity, mobile Internet access, remote monitoring and diagnostics, as well as enhanced safety and security are driving vehicle manufacturers and suppliers across Europe to seek out new wireless technologies. According to a recent research report on automotive telematics by Frost & Sullivan, wireless technology integration strategies would enhance the value proposition of vehicles by integrating advanced electronics systems such as infotainment systems, safety and stability systems as well as comfort and convenience enhancement systems. The total market size reached more than €279 million in 2008, and this is estimated to triple to nearly €900 million by 2015. Apart from this, there is room for a high number of new entrants in the advanced telematics and driver assist markets

2. The Connected Cruise Control project

In order to provide the driver with a support system for tactical driving tasks in the near future, the Connected Cruise Control system will have to be based on a combination of existing technologies, that can be retrofitted in existing vehicles. The system will not intervene in the vehicle control, but instead it will have to provide information and/or advice to the driver, which raises the question how the information needs to be conveyed so that the driver will exhibit the desired behavior, by adapting speed, headway or changing lane.

The CCC system is based on traffic flow models using information from roadside systems as well as floating car data. The traffic advice is added to the functionality of in-car systems for driver support functions that are part of the CCC system. In this way the CCC module will provide immediate value for money for the driver. The CCC system is created on a new technology retrofit platform with 3,5 G communication capability, an advanced digital map, an intelligent camera, vehicle data from the CAN bus and data from a traffic management centre.

A breakthrough innovation like CCC cannot be developed in one go. The Connected Cruise Control project aimed to find answers to the following research questions to support the development of the CCC and deliver proof of its effectiveness.

- What is the overall architecture of the CCC system, consisting of a navigation function, an intelligent camera, communication, traffic data and information and Human Machine Interface (HMI)? This question was addressed from a systems engineering point of view, starting with architecture concepts developed in EU funded projects.
- How can data from the intelligent camera, CAN bus (e.g. motions from in-vehicle sensors), digital map, GPS and traffic be integrated into a digital representation of the near vehicle environment (so-called Local Dynamic Map)? This question was addressed by a combination of system integration, communication and data fusion.
- How can the CCC system lead to a reduction of congestion? This question was addressed by developing traffic flow models based on floating car data and data from inductive loops and by studying the impact of the CCC system on traffic flow. A specific point of attention was the compensation of latency of the information using traffic flow predictions.
- What are the main functionalities of the CCC system? In this project we focused on providing advice on speed, headway and lane use, in which the information from in-vehicles systems and traffic management information is combined.
- How should the Human Machine Interface be designed in order to combine and reconcile advices for the local vehicle environment and the traffic environment? This question was addressed from a psychological perspective using a driving simulator to study the driver response and acceptance to CCC using different HMI designs as well as a field trial.

The project produced the following results:

- An architecture, interface specifications and software solutions for CCC systems, including in-vehicle and road-side components and the connecting communication infrastructure.

- A demonstrator CCC that provides advice on speed, headway and lane use. It was based on in-car telematics platform, including incremental map updates, a central processing unit with 3.5G communication capabilities, vehicle dynamics and control data from the CAN bus, an intelligent camera for lane departure warning, headway monitoring, speed sign and brake light recognition. Traffic data and traffic information were received from a traffic management centre.
- Vehicle and local environment estimation for a local advice for speed, headway and lane use.
- Traffic flow state estimation models based on floating car data as well as inductive loop data, an algorithm to provide an individual real-time advice for headway, speed and lane use and traffic simulation software to study the impact of CCC on congestion.
- HMI recommendations for presentation of the advice to the driver and assessment of the user acceptance.

The architecture and implementation of CCC is based on the framework of Figure 1. The CCC architecture does not only facilitate the integration of current CCC components, but is open, interoperable and flexible to accommodate further migration of the components and new functions. The architecture was based on existing architectures (CVIS, SPITS) that are supported by many partners from the automotive and traffic systems industry. At the core of the CCC system is a new generation on board unit with 2-3.5 G mobile internet communication.

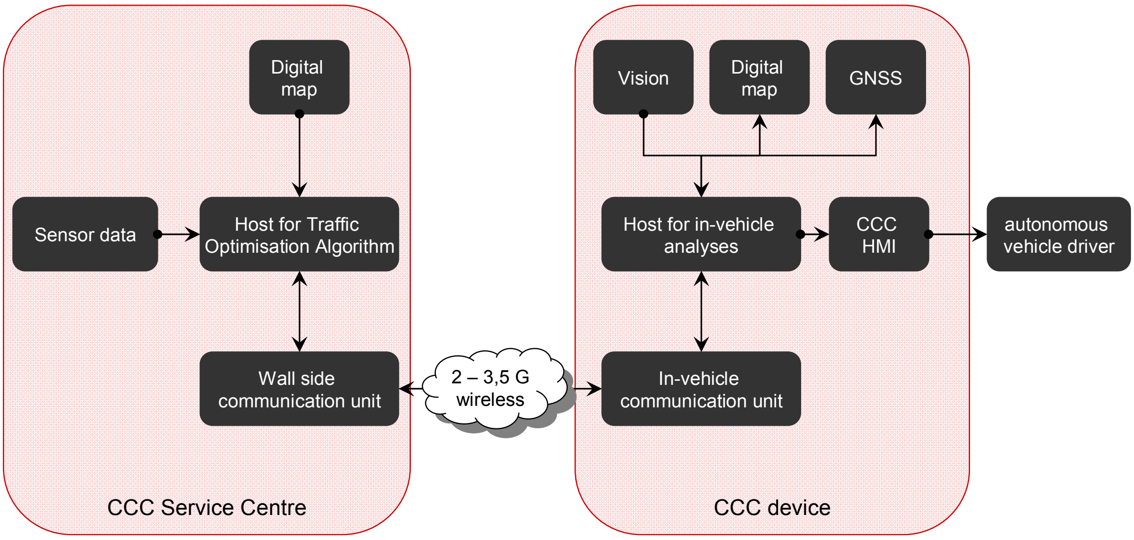

Figure 1: Connected Cruise Control architecture

At the road side, the traffic management center receives data from inductive loop detectors in the road as well as floating car data (i.e. information transmitted from equipped vehicles). Traffic flow models will be used to determine the advised speed, headway and lane use in order to reduce congestion. Floating car data added to the system will enable enhanced traffic state estimation to include local traffic flow dynamics. In order to compensate for latency in the road side data (about 2 to 3 minutes) and floating car data (latency possibly 2 minutes) traffic flow prediction models will be used. Before integration in the traffic management centre, the models will be developed in a simulated environment. This environment is also used to determine the potential impacts.

In the vehicle, an improved assessment of the vehicle and its environment was developed based on fusion of data from dynamic map updates, from the intelligent camera and vehicle dynamics and control data through the CAN bus. The combination of vehicle dynamics and control data, dynamic map updates and data from the intelligent camera enables new functions such as enhanced lane positioning, curve speed warning, local speed limit detection, brake light detection and pedestrian detection. The CCC application integrates the advice from the road-side for speed, headway and lane use to reduce congestion with a local advice for comfort and safety based on the fusion of data in the vehicle. A human machine interface (HMI) was developed to optimize the response by the driver.

3. Telematic architecture and system integration

Functional design principles for Connected Cruise Control.

CCC constructs its advice from assessing the downstream traffic conditions on three geographical levels: local vehicle level, downstream traffic flow level and road network level (Figure 2).

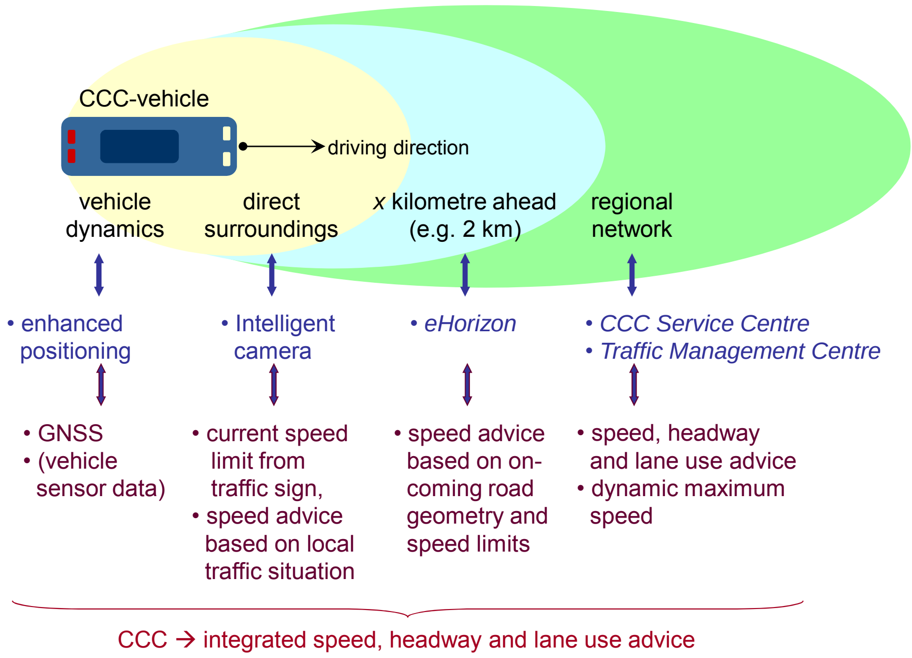

Figure 2: CCC constructs its advice on three geographical levels

At the local vehicle level, lane level vehicle positioning is essential to generate lane specific CCC advices. Using GNSS and the camera, the vehicle location will be determined with the specific lane it is driving on. In case CCC will be connected to the CAN bus, multi-modal sensing techniques can be added using data from vehicle sensors. The camera will also be used to observe the direct surroundings of the vehicle, i.e. road curvature, obstacles and the distance and relative speed to close in path vehicles. These observations will be used to define a safe driving speed and headway for the vehicle in its direct context.

At the downstream traffic flow level, the established vehicle position will be map matched on the digital map. From there the eHorizon will be constructed, yielding the most probable paths forward and the road attributes coming with these paths. The eHorizon will be used to define a safe and efficient speed and an appropriate traffic lane that fits with the on-coming road conditions (lane drops, curvature, slope, intersections, et cetera).

At the road network level, the CCC service centre receives data from inductive loop detectors in the road as well as floating car data (i.e. information transmitted from equipped vehicles and/or handheld nomadic devices). Enhanced on-line traffic flow models will be used to determine local traffic flow dynamics and to derive the advised speed, headway and lane use in order to reduce congestion. Since the tracks of individual CCC vehicles are monitored, these advices can be parcelled and tailored to these vehicles. In the meanwhile the Traffic Management Centre (TMC) might adjust the speed limits dynamically to the traffic, weather, and/or environmental conditions. The dynamic speed limits will be communicated with the vehicle directly or via the CCC service centre.

In the vehicle the final advice will be constructed by fusing the: (i) safe speed and headway based on the intelligent camera observations, (ii) safe and efficient driving speed and traffic lane derived from the eHorizon, (iii) advices from the CCC service centre and (iv) dynamic speed limits from traffic management centres (TMC). This is illustrated in Figure 3. A dedicated human machine interface (HMI) will be developed to optimize the response by the driver.

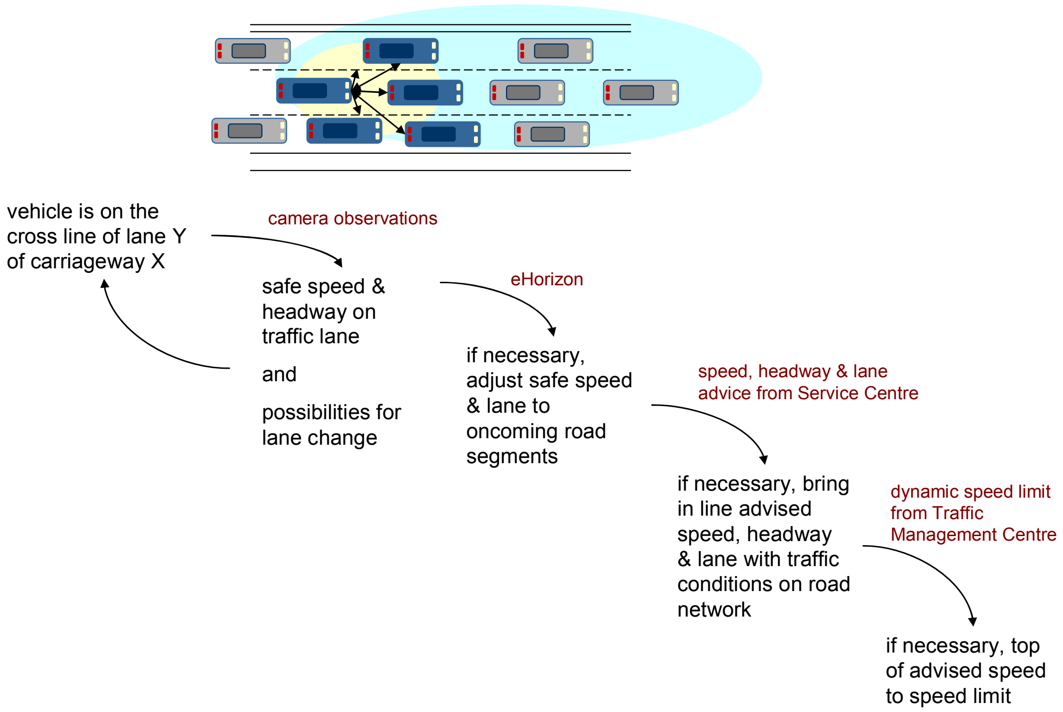

Figure 3: Fusion of advices within CCC

Required characteristics of the CCC architecture and interface specification

The CCC architecture and interface specifications provide the following characteristics:

- (Openness) generators of services can deploy their services on mobile units that are financial and road safety grade;
- (Trustworthiness) run multiple services amongst which CCC on one mobile unit under guarantee that the services do not interfere with each other;
- (Interoperability) deploy services over borders of road operators in the European Union member states with one contract, on one mobile unit (on-board equipment) for a Service User;
- (Flexibility) different technical implementations are possible within the same architecture; in other words, the architecture and interface specifications do not prescribe a singular technical implementation.

The architecture guides designers and developers in providing these characteristics with their GNSS enabled telematics platforms.

Required grades of the enabling telematics platform

CCC is a road safety related service. CCC itself comes with a service for digital rights management (e.g. to pay for updates of the digital map). CCC might be combined with road user charging to create an uplift in the market penetration. To enable a wide spectrum for services, CCC's enabling telematics platform should provide a 'road safety grade' and 'financial transaction grade'. These grades give expression to different groups of services (and corresponding stakeholders) and – although coming from different angles – both put high claims on the enabling telematics platform. These claims are:

- guaranteed capabilities:
  - availability of the mobile unit;
  - end-to-end security (end-to-end secure communications, secure environment for processing and storing of data);
  - accurate and precise positioning;
  - bandwidth and maximum latency in communications;
  - CPU capacity;
  - (volatile and non-volatile) memory capacity;
- guarantee that none of the services will interfere with or impact on the integrity or performance of the road safety related services (more generic: usage based charging services).
- guarantee that none of the services will interfere with or impact on the integrity or performance of the road safety related services
- services are not allowed to intervene with the in-vehicle systems (in other words, CCC does not support advanced driver assistance systems).

The architecture guides designers and developers in providing these guarantees with their GNSS enabled telematics platforms.

Embedding privacy, security and fault tolerance

To embed privacy, security and fault tolerance, the design of the enabling telematics platform should meet the following design rules:

From privacy perspective:

- operate a service without using personal data if possible;
- personal data must be collected for explicit and legitimate purposes and used accordingly;
- personal data must be relevant and not excessive in relation to the purpose for which they are processed;
- process personal data fairly and lawfully;
- safeguard that personal data is accurate and kept up to date;
- safeguard that personal data that identifies individuals is not be kept longer than necessary.

From security perspective:

- set up a circle of trust between cooperating actors and their units or centres;

- protect data;
- provide end-to-end security in communications.

From safety perspective:

- unambiguously demarcate the field of application of a service;
- guarantee interoperability of service operations;
- tune the service operations to the penetration rate of service users.

From fault tolerance perspective:

- follow predefined structuring rules in the cooperations (collaborations);
- manage the latency in service operations;
- manage an appropriate usage of the available resources in the unites and centres;
- safeguard the integrity of data;
- safeguard the validity (‘up-to-date’-ness) of data;
- manage the availability of the communication bearers;
- services are not allowed to intervene with the in-vehicle systems (in other words, CCC does not support advanced driver assistance systems).

CCC from a service perspective

To make CCC operational on a 24/7 basis and compliant to the functional and non-functional principles as outlined above, a whole ecosystem needs to be set up (and paid for). An ecosystem, in which different suppliers and manufacturers contribute on commercial basis to an operational CCC service, where (figure 4):

- At the first tier service providers offer CCC as a service to customers. This can be end-users who consume CCC directly or companies who use CCC as a business enabler.
- At the second tier content providers provide traffic data that can be used by CCC service provider(s). Digital map providers provide high accuracy digital maps and a dynamic map update service. Manufacturers bring CCC compliant in-vehicle devices to the market.
- At the third tier, semiconductor companies bring high quality and affordable (integrated) ITS chipsets on the market and manufacturers bring high quality and affordable intelligent cameras to the market. Service application developers develop CCC applications.

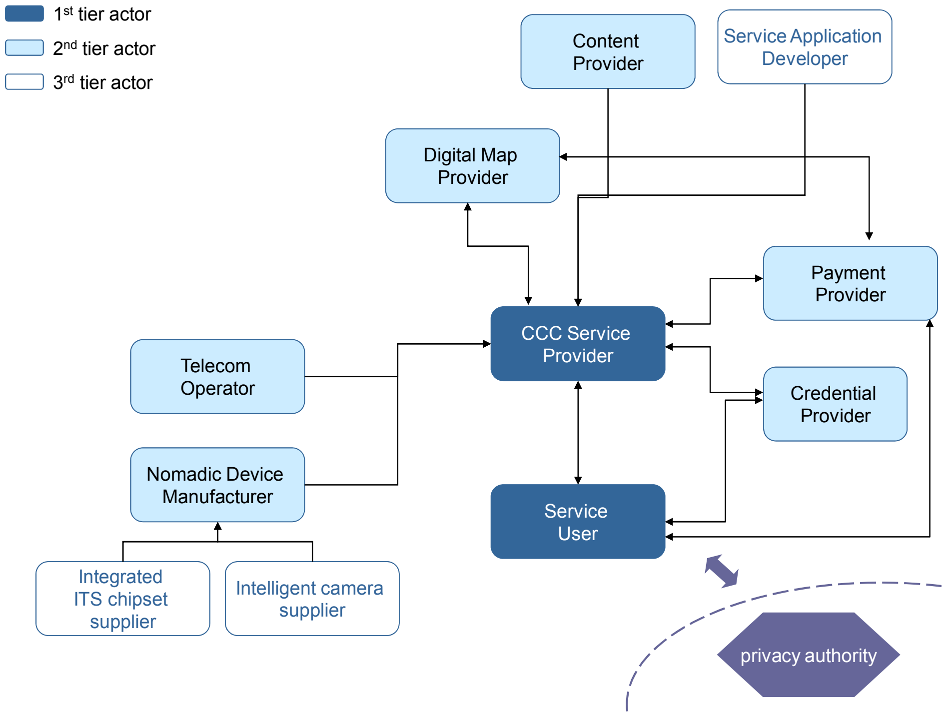

Figure 4: Organizational viewpoint of the CCC ecosystem

CCC from a systems perspective

The full CCC system contains a central (road side) subsystem and an in-vehicle subsystem (mobile unit). This is illustrated in figure 5. Innovative technologies that will be integrated in CCC are: intelligent camera, high accuracy digital map and eHorizon and an integrated ITS chipset.

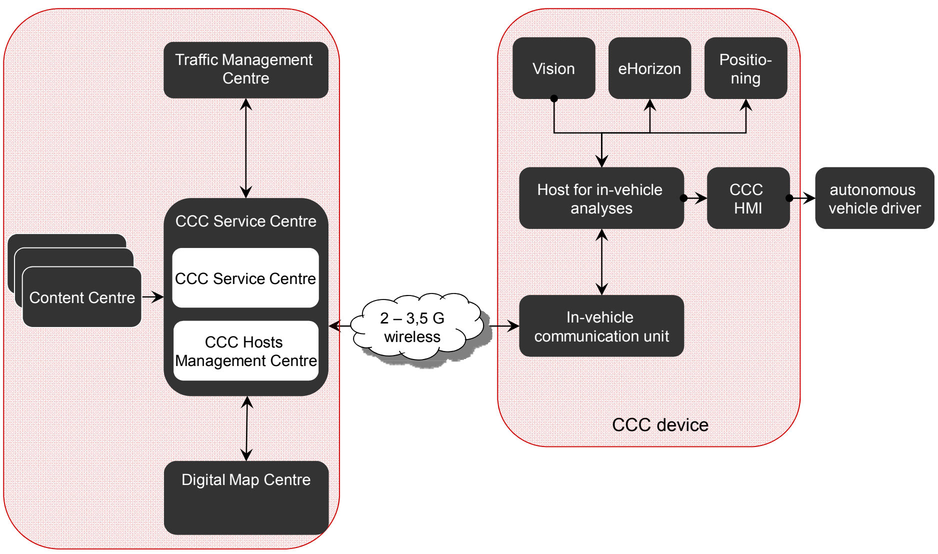

Figure 5: Construction scheme of the CCC system

CCC uses an advanced monocular camera that acts as an extra eye, actively assisting the driver by continuously watching the road, increasing his/her security, and decreasing the risk on accidents. A high accuracy digital map is the enabler of the eHorizon. CCC will work with an integrated ITS chipset, aimed to support a rich set of components (2 / 3.5G communication, GNSS, run time environment, working memory, memory for digital map storage, secure environment for ‘payment’ of map updates, et cetera) and an attractive consumer price. CCC will work with 2 / 3.5G cellular communications that is commercially available in European countries, especially in the areas with where people live and the road network is rather saturated.

Implementation of CCC

The implementation of CCC was done using the following components as in table 1.

Table 1: CCC components

CCC Service Centre		
	Service Centre	Technolution hosting centre, running the traffic optimisation aplication of the TU Delft
	Host management centre	Technolution hosting centre connecting to the CCC device in the test vehicle
	Digital Map Centre	Nokia/Navteq’s digital map centre
	Content Centre	NDW (National Data Warehouse for road traffic data)
	Traffic Management Centre	Regional traffic management centres of Rijkswaterstaat for dynamic speed limits: • Northwest Netherlands; • Southwest Netherlands; • South Netherlands.
CCC Device		
	In-vehicle communication unit	ATOP of NXP
	GNSS	In the preliminary tests a stand-alone version of the ATOP of NXP In the final test: the positioning device coming from WP4 - TNO, including the ATOP of NXP
	Host for in-vehicle analyses	Mobiboxx of Technolution
	eHorizon	Mapping and Positioning engine and corresponding digital map of Nokia/Navteq
	Vision	The current off-the-shelf Mobileye platform
	CCC HMI	Samsung Galaxy tab connected via Bluetooth tot the Host (i.e. Mobiboxx)

The building plan for the implementation of the CCC device is depicted in figure 6.

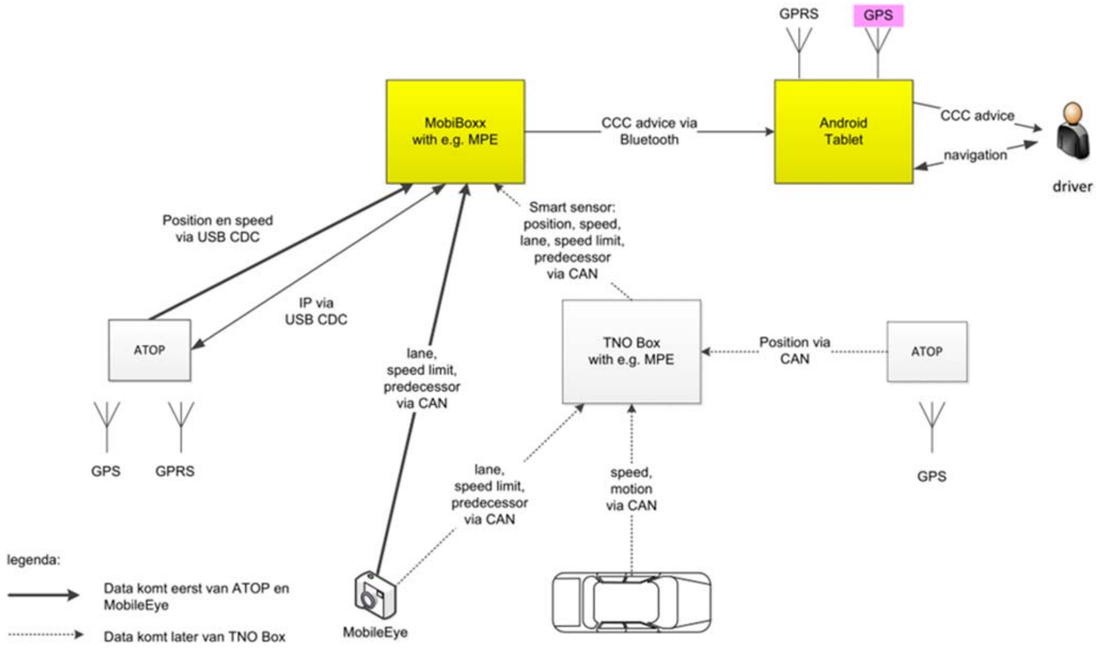

Figure 6: Building plan for the implementation of the CCC device

Realization

The complete system was build and field tested from November 2012 till February 2013. The technical performance of the CCC system as outlined above was in line with expectations. The central server infrastructure calculated the speed and lane advice based on a number of attributes. The result was communicated over the 2.5G gateway to the on-board unit (OBU) in the vehicle and was shown to the driver on the tablet in the car. The calculations on the server and communications to the driver worked as specified. Figure 7 displays a view of the in vehicle system.

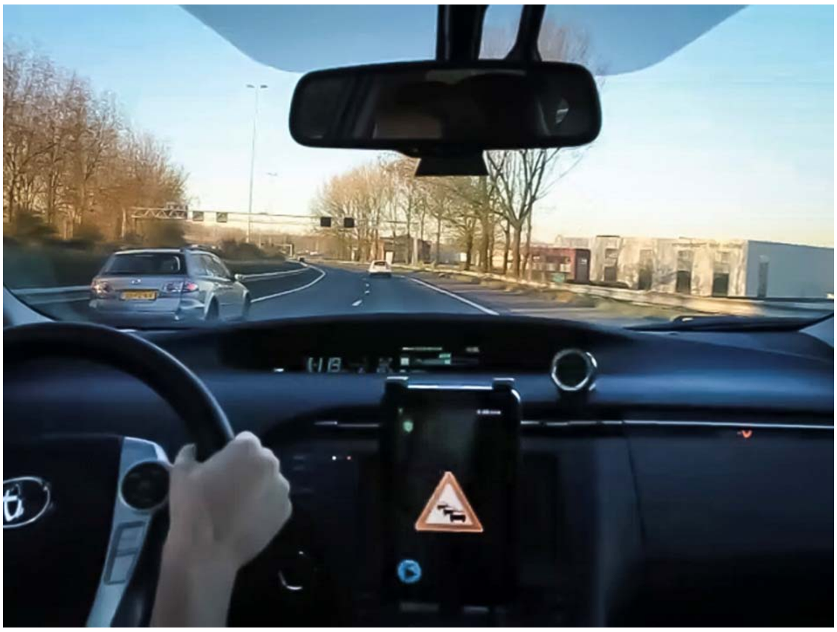

Figure 7: The In vehicle system during the field trial

Areas for further investigation either in system hardware or sensor/attribute information:

- Data from the RWS server has an irregular latency of anywhere between 0-4 minutes between the moment the speed/traffic sign is set above an individual lane and the moment the signal is delivered over the gateway to the CCC server. This is an area that needs some more reliability testing the signal has been operational since late 2012.
- The camera functionality of the forward looking vision system was tested in a separate stand-alone setup not integrated in CCC configuration listed above.
- The incremental update functionality for the MPE was developed and successfully tested in an off-line setup. The functionality is currently in development for production ready systems.
- Position at lane level will require further work. In addition to the fusion of GNSS, map and camera data, explorative experiments were done on Precise Point Positioning using a common GPS system and predictions of satellite orbits and atmospheric conditions.

4. In-car and road side platform

The on-board unit (OBU) was developed based on a processing host for in-vehicle analyses, an in-vehicle communication gateway and an HMI user interface device. The on-board unit accommodates the software modules that are developed in the project. Additional software was developed for fusion of data from the intelligent camera and data from the map database, for speed limits, lane information and other relevant data elements. A software component for tile based over the air incremental map updating was developed for implementation in the OBU. The roadside platform was based on a central server infrastructure including a communication component as gateway to a large number of vehicle platforms (OBUs).

Figure 8: CCC system overview

The CCC OBU requires a rich set of components: 2-3G communication, GNSS, run time environment, working memory, flash memory for digital map storage and all at an attractive end-consumer price point. To overcome the complex architecture, CCC uses an integrated ITS chipset (NXP-ATOP) with a connected host platform providing flexibility in processing power and software featuring to run Nokia MPE software. The host contains the digital map data and provides the connection to the HMI. The HMI is a Samsung Galaxy tab running the Nokia Location Platform for map display and routing software.

ATOP

The ATOP was developed by NXP as enabler for telematics mass market services to drive the adoption of telematics communication in vehicles. The ATOP platform is equipped with a baseband microprocessor for customer applications and a connectivity processor as well as a GPS receiver, a security and NFC processor for e.g. driver-identification. The NOKIA MPE eHorizon application and digital map storage is provided by the ATOP using the external host.

Mobibox Host

The Mobibox platform was used as host for the ATOP. The ultimate ambition of CCC was to run all the software at the vehicle side on the ATOP. The NOKIA MPE calculates real-time the electronic horizon while driving. The CCC algorithms retrieve and process the data from the intelligent camera, the electronic horizon and the advice from the server. From this data a tailored speed, headway and lane advice are derived for the vehicle driver. Some of the building blocks mentioned were moved from the ATOP onto the host for efficiency reasons.

Intelligent camera

CCC uses an advanced camera that acts as an extra eye, actively assisting the driver by continuously watching the road, increasing security, and decreasing the risk on accidents. CCC is using a revised Mobileye C2-270 camera platform. Software was developed for fusion of data from the intelligent camera and data from the map database, concerning speed limits, lane information and other relevant information elements, and integrated on the OBU.

Map & Positioning Engine

The Map and Positioning Engine (MPE) reference design consists of the MPE Reference Software and the MPE Map.

The MPE reference solution software includes key modules required for the functioning of the MPE. These include Map Access Layer, GPS Position, Map-Matching, and Electronic Horizon. The core of the MPE is the Electronic Horizon algorithm that enables a vehicle's on board system to search for and interpret attributes ahead on the road and give the driver and vehicle sensor systems predictive road information required to aid driving decisions and the system's response. Typical attributes might be curvature, height and/or slope, speed limits, hazard zones, etc. Application examples can be found in the Driver Information, Active Safety and Energy Efficiency domain.

The MPE map contains a subset of the full digital map database, specifically suited for ADAS applications. It will not serve the purpose of turn-by-turn route guidance. The map database is platform independent and can be used in all hardware platforms. It includes high precision geometry, curvature and height/slope. The data consists primarily of nodes, links, link attributes, and link geometry. Shape points are used to represent the link information in more detail. The map database uses the WGS84 coordinate system, so any point on the earth's surface, except the North and South Poles, is uniquely identified with a point (x, y) in the coordinate plane.

Central server infrastructure

Managed motorways use methods to increase peak capacity and smoothing traffic flows on very busy major highways. Techniques include variable speed limits, hard-shoulder running (spitsstroken) and ramp-metering controlled by overhead variable message signs. Rijkswaterstaat (RWS) uses the Motorway Traffic Management system (MTM) to manage the Dutch motorways. MTM has a subsystem called the TOP (Transaction Oriented Processor). An instance of the TOP runs in each of the five regional traffic management centers of RWS in the Netherlands. Over the last year a new interface, called NINA gateway, has been created on the TOP in order to pass through the current signs information on the variable message signs above the traffic lanes. Experiments in CCC during Intertraffic 2010 have shown the possibility to retrieve data via the NINA gateway and pass the current signs on via a service center to vehicles on the road using a 2.5G link. In the context of CCC, RWS has opened this NINA gateway. Via this gateway the dynamic speed limits will be retrieved as they are set on the Variable Message Signs at that very moment.

5. Fusion of in-car data

Fusion of in-car data

Production vehicles are equipped with a growing number and variety of sensors. Also Smartphones and dedicated navigation devices contain a multitude of sensors. This section describes the development of methods for combining signals from different sensors (i.e. sensor fusion), mainly aimed to provide a reliable position reference base for the CCC application. A distinction can be made for using access to the vehicle CAN bus or to rely on vehicle independent signals only. The vehicle CAN bus provides wheel speed and steering angle, which can be used to improve the performance of the positioning method in terms of reliability and accuracy. In general, connecting to these CAN bus signals is (currently) not possible without involvement of the OEM. TNO had already developed a secure access to the CAN bus for a Toyota Prius III, and therefore this vehicle type was chosen for the developments. An overview of sensors and signals available for the positioning method is provided in Table 2.

Table 2: Overview of sensors and signals used in sensor fusion method

Sensor	Signal	Information	Use
CAN bus	Steer angle	Wheel orientation	Lane change detection
	Wheel speeds	Vehicle speed and cornering	Position enhancement
	Lateral acceleration	Vehicle cornering	Lane change detection
	Yaw rate	Vehicle cornering	Position enhancement and lane change detection
GPS receiver	Longitude/latitude	Position	Position enhancement
	Ground speed	Vehicle speed	Position enhancement
	Heading	Vehicle cornering	Lane change detection
Mobileye camera	Left Lane available	Existence left lane	Lane level positioning
	Right lane available	Existence right lane	Lane level positioning
	Distance to lines	Vehicle position in lane	Lane change detection
ADAS map	Number of lanes	Number of lanes	Lane level positioning

The test vehicle (see Figure 9) has been equipped with additional sensors in order to obtain a reference base of the positioning method. Experiments have been carried out on several proving grounds and on public road.

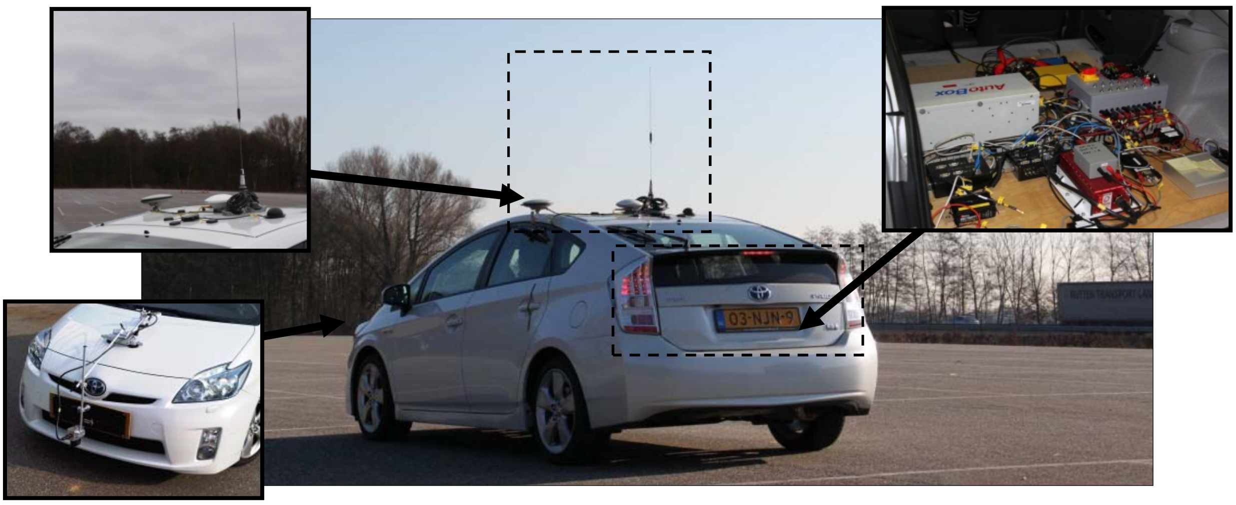

Figure 9: Test vehicle with full instrumentation for proving ground experiments

The sensor fusion concept is developed towards lane level positioning following the steps described in the sections below.

Vehicle state estimation

The concept of vehicle state estimation has been used for position enhancement in terms of absolute longitude and latitude coordinates. The vehicle state estimator contains a so-called prediction model, which is a representation of the vehicle and installed sensors. A series of driving tests was been conducted on the ATP proving ground (see figure 10) to identify the prediction model, and to obtain reference data for vehicle position.

Figure 10: Proving ground used for vehicle state estimation development

The vehicle state estimation (setup depicted in figure 11) uses vehicle signals from the CAN bus (steer angle and wheel speeds), measured motion signals (yaw rate, lateral and longitudinal acceleration) and GPS positioning signals (longitude and latitude). The reference position is obtained from a so-called Real-time Kinetic (RTK) system that uses a radio beacon to provide a position with an accuracy of 2 cm.

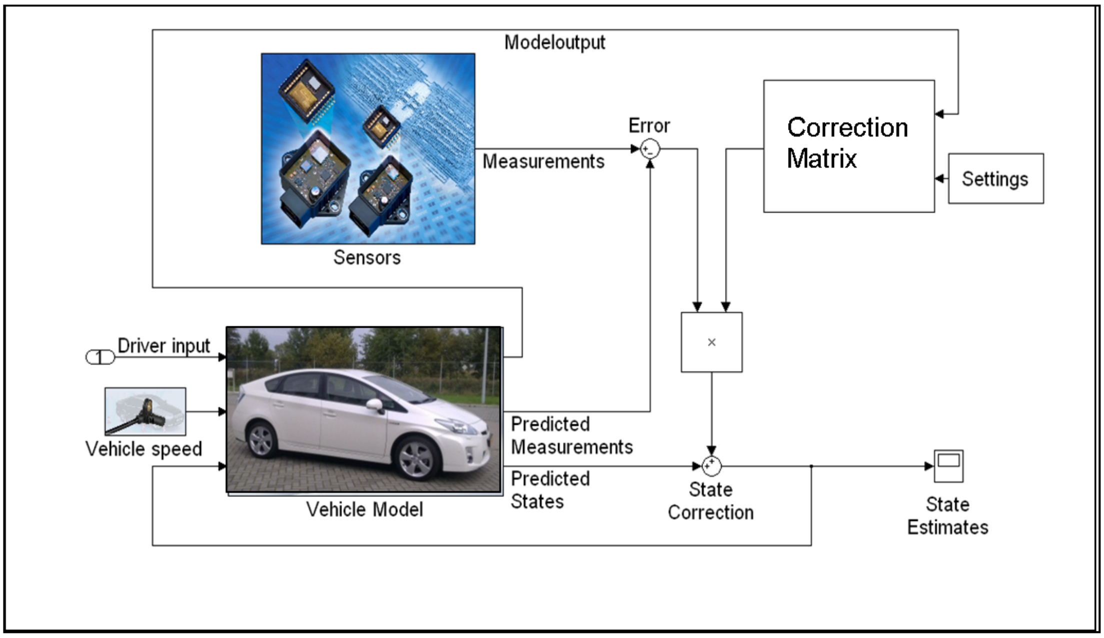

Figure 11: Setup of vehicle state estimator

The position inaccuracy of raw GPS is caused partly by latency in the signal of about 0.8 seconds, and furthermore the GPS update rate is limited to 1 Hz. The sensor fusion concept corrects the latency and provides a 100 Hz update rate. Furthermore the position signal obtained from sensor fusion is smoother. Figure 12 shows a comparison of customer grade GPS receivers and the sensor fusion solution (the NXP ATOP is indicated Sensor 1).

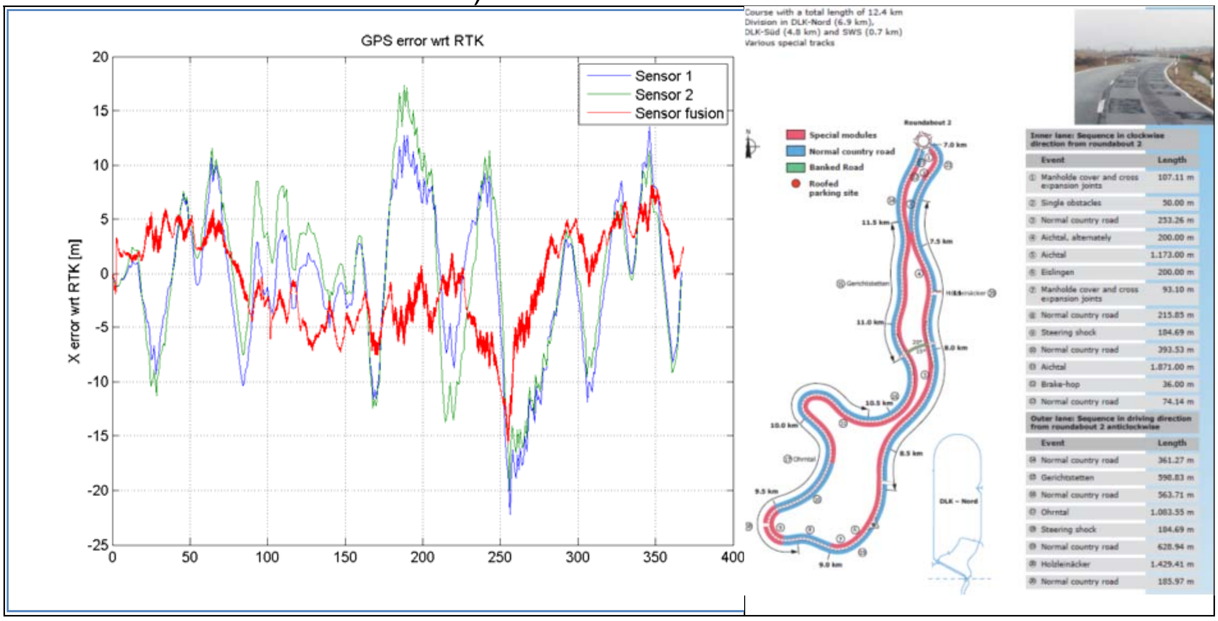

Figure 12: Sensor fusion solution compared to customer grade GPS sensors (Sensor 1 = ATOP)

E-horizon map

The ADAS Map includes so-called E-Horizon information. The information used for the HTAS-CCC application is the number of lanes and speed limits for road sections. The Mobileye camera detects speed signs and to a certain extent the number of lanes. The camera information is available real-time and can be used to update the E-horizon content that may have changed since the map was created, or to account for temporary situations such as road works.

The combination of ADAS map and Mobileye camera has been investigated on a route that includes the road selection used for user evaluation of the HTAS-CCC application (see figure 13). A special permit was arranged to drive the route at a fixed lane for testing. In total 4 sequences have been driven on the route, each time at a different fixed lane, roughly 8 hours of logging data. For this purpose the vehicle instrumentation was extended with a video camera for post processing of the recorded CAN messages from the Mobileye camera and the Navteq ADASRP 2009 hardware, which contains the ADAS map.

Figure 13: Test route for gathering data from camera and ADAS map

From the experiments it has been concluded that the number of lanes defined in the navigation map may not correspond to detections of the camera around merging on-ramps, or departing off-ramps. Additionally, the ADAS protocol defines the existence of emergency lanes which generally exist on the right of driving lanes, but on very wide motorways may also be present left of the driving lanes. Finally, emergency lanes sometimes are open for traffic (i.e. spitsstroken) which can be either on the right or left emergency lanes.

The Mobileye camera lane detection is limited to existence of left or right lane. An indication of lane marking type is provided but the lane markers are not consistently used on the road. For example in some cases a solid line is used when lane changing is not allowed, while more lanes are available (see figure 14).


Figure 14: Example of driving lanes with a variety of line markers

Lane level positioning

To achieve lane level positioning a combination of Vehicle State Estimation and E-Horizon map was applied. A lane change detection method was developed in order to keep track of the lane number in use for situations where the combination of camera and ADAS map is inconclusive. Three main sources of information were combined:

1. The Mobileye camera provides line crossing and other vehicles on the road.
2. The road shape from the ADAS map is combined with enhanced GPS.
3. Vehicle State Estimation provides motions resulting from driver input.

The method was developed using the test results obtained for the E-horizon map application, and from dedicated experiments on Helmond's a270 test site where an RTK reference position is available. Figure 15 shows some typical lane change detection results from the three sources of information. With the lane change detections added the lane positioning method has been successfully completed.

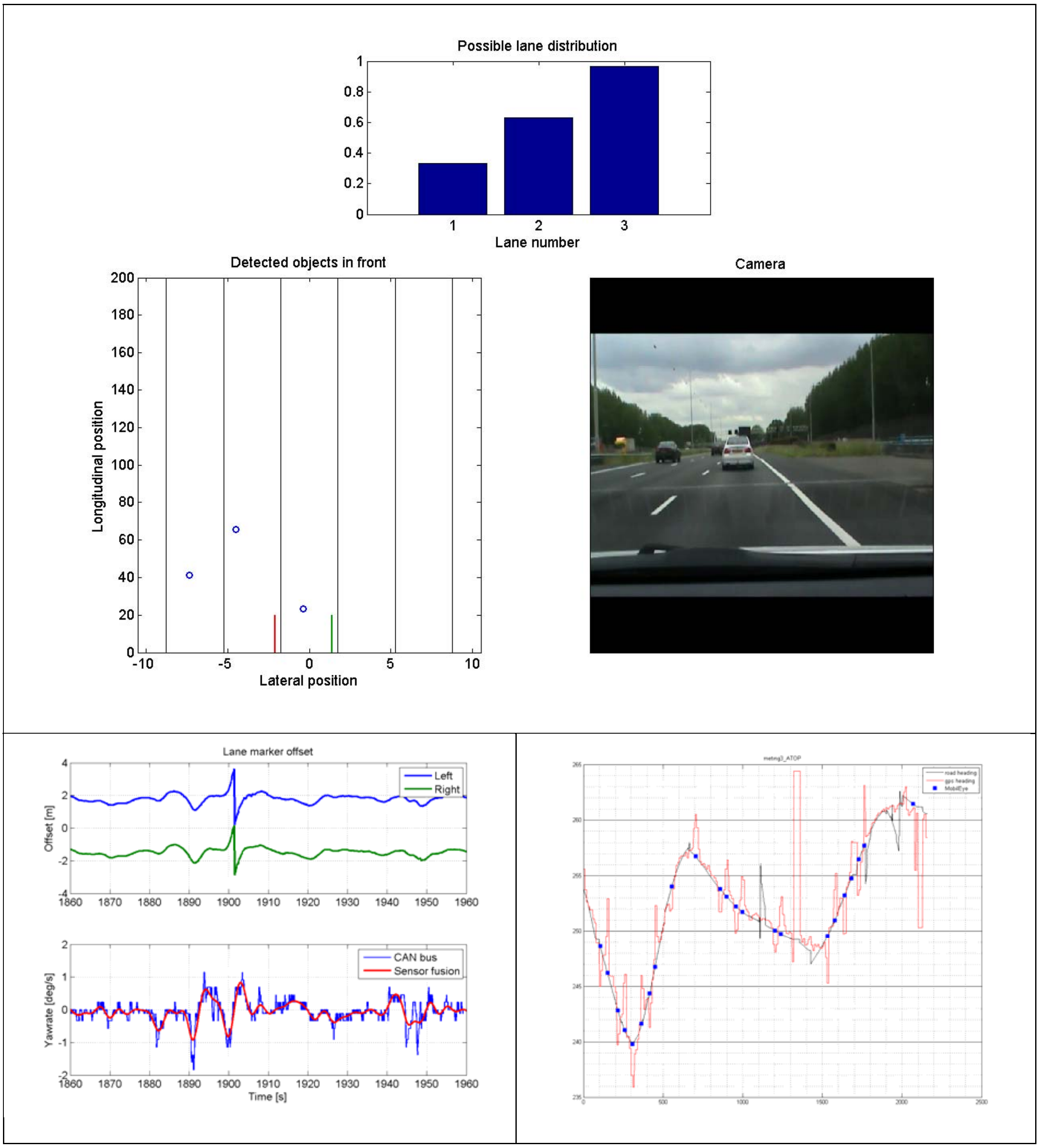

Figure 15: Lane change detection results

6. Connected Cruise Control Advice

The Connected Cruise Control system gives a speed, headway and lane use advice to improve traffic flow efficiency. This chapter describes the algorithms for traffic flow prediction and advice generation. It also reports on the development, calibration and validation of a traffic flow simulation environment that was used to test the CCC system, followed by a technical evaluation of the CCC system in traffic flow simulation. Finally, this chapter will report on the expected impacts of CCC on traffic flow efficiency and safety at different compliance and penetration level of CCC equipped vehicles using traffic flow simulation experiments.

Traffic state estimation using loop detector data and floating car data

The algorithm for traffic state estimation was developed, based on data from inductive loop detectors (speed, volume per lane) in the road as well as floating car data (e.g., position, speed). In order to compensate for the expected latency in the road side data (often up to 3-4 minutes) and floating car data (latency possibly 2 minutes) traffic flow prediction methods was used. The traffic state is estimated using loop detector data and floating car data. Loop detector data provides minute averages of intensity and speed. Floating car data provides the speed and position of individual vehicles. The two data sources are combined into a coherent estimated traffic state using an advanced data fusion filter as described in Schakel and van Arem (2012a). The filter accounts for the fact that traffic states move with different speeds depending on the state itself. Congested traffic states move backwards while free flow traffic moves forward.

Delays of the data that were experienced in tests are a delay of 75 seconds for the detector data and a delay of a few seconds for the floating car data. The advice algorithm (see next section) requires the traffic state one minute in the future. Consequently, the prediction of traffic states is less important than initially assumed as even without floating car data only 135 seconds needs to be overcome. Still, in order to give advice at an appropriate time and location it is important to know the location of (potential) problems one minute ahead requiring some form of prediction. To this end, the filter applied for traffic estimation, which already overcomes the data delay, can also be used to additionally overcome the required prediction time. Therefore, the traffic state is predicted by applying the traffic state estimation filter with a requested time of estimation of one minute ahead.

Road side speed, headway and lane use advice for traffic flow improvement

The advices are created based on an estimated traffic state of one minute ahead. This time allows drivers to follow-up the advice before they reach the (potential) problem. The advices are generated with the advice algorithm described in Schakel and van Arem (2012a). This algorithm implements a general approach where the network is split into (possibly overlapping) sections of merging, splitting or ending lanes. Based on this infrastructural information different triggers of flow and speed are defined which trigger different (sets of) advices to be activated in an area around the trigger. Note that traffic density is not used as a trigger as speed and flow data may show inconsistencies due to different sources being used. For example, floating car data may report low speeds at a location in between detectors, while traffic at the detectors is still at high flow (for the time being). In that case, the traffic state prediction finds low speed and high flow, resulting in unreasonable high densities. Therefore, advices are triggered either for low speed or for high flows.

Two different advice principles are used. The distribution advice principle triggers in case of high flow at a single lane and redistributes traffic over the lanes. Depending on the section, advices may be given in order to allow smoother lane changes, minimizing the disturbance on the busy lane and reducing the probability of traffic flow breakdown (i.e. traffic slowing down resulting in congestion). Such advices are given if infrastructure enforces lane changes such as at a lane-drop, weaving section or an onramp. A few examples of this are shown in figure 16.

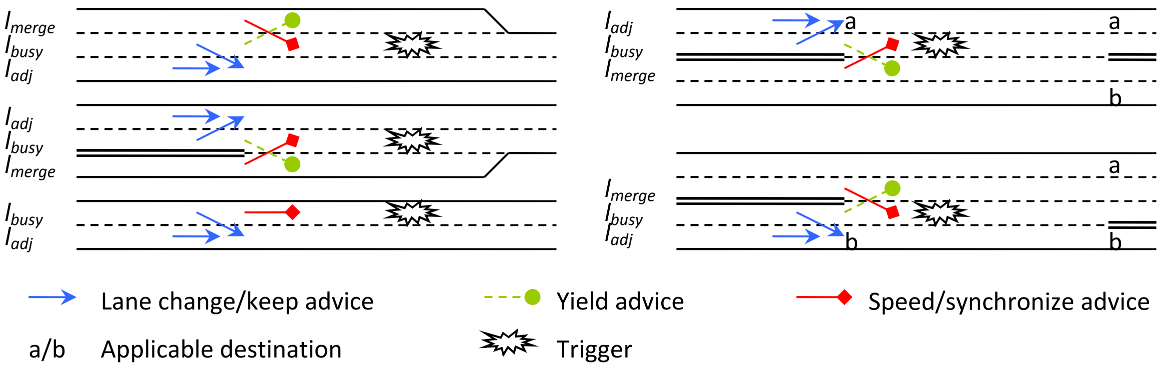

Figure 16: Typical examples of distribution advices.

The acceleration advice principle triggers with low speeds and advices drivers to maintain a short but safe headway during acceleration at the downstream end of congestion. This may reduce the capacity drop, i.e. the fact that outflow from congestion is lower than the maximum stable flow before traffic flow breakdown.

The advice algorithm is designed such that additional advice principles can be implemented within the algorithm. Possible overlap between advices from different advice principles are filtered by the advice algorithm.

Simulation environment for the impact of road side speed, headway and lane use advice on traffic flow

To simulate CCC with different penetration rates, a new simulation framework has been developed. As CCC uses a combination of system elements (server, on-board unit) which are not part of existing simulation software, a new framework called MOTUS[1] has been developed which allows the implementation of Intelligent Transport Systems using on-board units, road-side units and various controllers (e.g. traffic management centre, traffic light controller).

MOTUS includes driver models for lane-changing and car-following. Many models exist in literature, yet for CCC a new lane-change model has been developed which focuses on an accurate representation of:

- Lane distributions at different distances to off ramps, lane-drops etc.
- Realistic disturbance impact of lane changes based on the relaxation phenomenon which is that drivers accept small gaps during a lane changes after

[1] At the time of writing, MOTUS is available from http://homepage.tudelft.nl/05a3n/.

which the headway is slowly increased to regular values. This also pertains to the vehicle which is changed in front of.

- Realistic impact on speed at a lane of vehicles that slow down as lane change preparation in case their target lane is slower, i.e. speed synchronization.

These phenomena are important as they pertain exactly to aspects of traffic flow which CCC aims to improve. The Lane-change Model with Relaxation and Synchronization (LMRS) was developed to model these phenomena and is described in Schakel et al. (2012b). It is combined with the car-following model IDM+, which is an adapted version of the Intelligent Driver Model (IDM). The IDM+ has a more realistic capacity while the good traffic stability properties of the IDM remain. The IDM+ is described in Schakel et al. (2010).

CCC has been implemented within MOTUS including the modules that run on the server for the traffic state prediction and the advice algorithm. These modules have been developed in a simulation environment but are also largely implemented on the actual server. To facilitate a parallel development of the modules and other parts of the actual system, interfaces between the modules on the server have been defined. These describe what information is given from one module to the other.

Technical evaluation of the CCC prediction and advice algorithm in simulation

The prediction and advice algorithms have been developed in the simulation environment MOTUS. In this way, large scale implementation of CCC has been tested and found to be working without error. The calculations for the algorithms regarding a 10km 2 or 3 lane road take in the order of one second which allows live implementation. The algorithms have also been tested in small scale on a real server. The parts of the algorithm designed specifically for the real server, as well as the parts also used in simulation, successfully communicate with the other parts of CCC using the defined interfaces.

Whether the prediction and advice algorithms produce logical and reasonable results was validated visually from simulation. The predicted speeds in simulation in different parts of the network coincide for the most part with the actual speeds in simulation. Especially in case of a sufficient penetration rate (and thus floating car data), there is no significant delay between traffic flow breakdown and a predicted low speed. Areas where advices are given have also been visually validated to be logical. The location and time of advices coincides with the triggers as defined for the different advice principles, i.e. the traffic state estimation (from which the triggers are evaluated) performs as expected. The filter of advice regions is able to prevent overlap. Examples of where and when advices are given are shown with black dotted vertical lines in figure 17. The left figure shows speed and the blue/violet regions are areas with low speeds. The acceleration advices are given at the downstream end of these areas. The right figure shows flow, and distribution advices are mainly given within or upstream of high flow (red) areas.

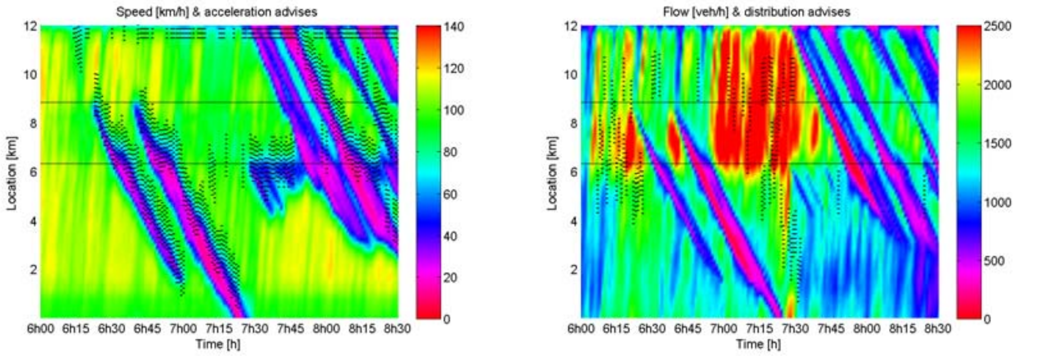

Figure 17: Acceleration advices and traffic speed (left) and distribution advices and traffic flow (right) on the 2nd lane from the right on the A20 from Prins Alexander to Gouda in simulation.

Impact on traffic flow

An exploratory micro-simulation study on the study area was performed with the micro-simulation tool ITS modeller as developed by TNO, in combination with the Lane change Model with Relaxation and Synchronization (LMRS) (Schakel, et al., 2011) to implement the CCC advices. Three advices given to drivers were tested on several lanes: a lane change advice to change to the lane at the right, a headway advice and a speed advice. A compliance rate of 100% was used. It was found that a lane change advice and a headway advice to CCC drivers on the middle-lane in combination with a speed advice to CCC drivers on the left-lane have the largest positive effect on traffic flow. These advices show positive effects for all tested penetration rates. The smallest tested penetration rate, 2%, showed a small positive effect. With a maximum penetration rate of 40%, an increase of maximum flow of 4% was found and a vehicle loss hours reduction of 68%. (Harmsen 2011, Schakel et al., 2012c).

Next, the impacts of CCC on traffic have been investigated in simulation with MOTUS by running CCC with recorded data from two different days. For each day, the penetration rate and compliance rate (the extent into which drivers adhere to the advice) have been varied to investigate what levels have what impact. The test area for the simulation as well as the test drives is given in figure 18. The evaluation is described in Schakel et al. (2013).

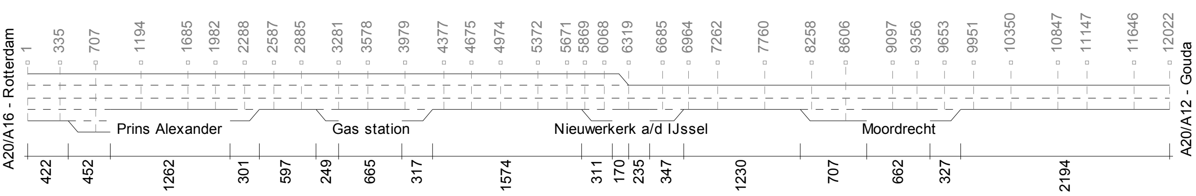

Figure 18: Schematic representation of test area

Figure 19 shows the travel time delay for two different days and for various levels of penetration and compliance rate. The advices have a significant influence on travel time delay already for small rates. However, on one day this is a positive influence (less delay) while on the other day this is negative. It is expected that redistributing traffic from the middle to the right lane because of the lane drop may have adverse effects in relation with disturbances from the nearby on-ramp Nieuwerkerk a/d IJssel and the off-ramp Moordrecht, which often has spillback, i.e. congestion growing on the off ramp and reaching the freeway. For rates of 10% or higher the impacts vary from little change to large positive change. This is due to the acceleration advice principle of which the effectiveness increases steadily as the change of blocking by predecessors reduces.

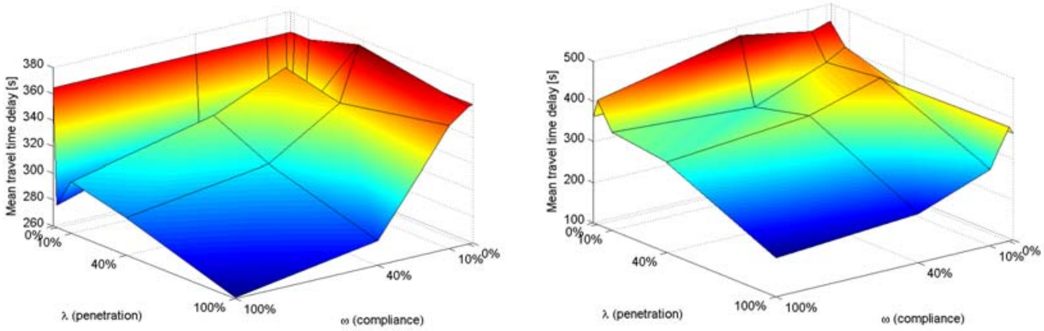

Figure 19: Mean travel time delay on two different days for various levels of penetration and compliance rate.

In summary, it was found that CCC lead to a slight increase of saturation flow and capacity, with delay time savings up to 28% and 46% for the days that were simulated. Further research is required however to moderate the interaction between the advices at the lane drop and the off-ramp.

Impact on traffic safety

To investigate if CCC would also affect road traffic safety, a preliminary analysis of possible road safety effects was executed in the context of a Master Thesis project (Van der Gulik, 2012). This section summarizes the results of this Master Thesis that consisted of two parts.

In the first part of the Master Thesis research, possible road safety effects were identified by means of a HAZOP-brainstorm. The HAZOP-method is a structured brainstorm process that identifies hazards and operability problems (Jagtman, 2004). The HAZOP-brainstorm with four employees of SWOV, TU Delft and TNO resulted in a list with possible deviations from the intended operating process of CCC. Roughly the effects identified were categorized into two types of effects:

- Effects related to changes in traffic flow, e.g. changes in driving speed patterns, headway patterns and lane change patterns
- Effects related to the driver, e.g. distraction and an increase of workload

The second part of the research focused on the effects related to changes in traffic flow. Using the microscopic simulation model developed by Schakel et al. (2012b), the effects of different penetration levels of CCC were examined on a number of road safety indicators for a part of the A20 highway. For the examined stretch of highway, the following road safety effects were found:

- Speed-related indicators showed that CCC resulted in a reduction of congestion. This might be positive for traffic safety as congestion often involves shockwaves that have a negative impact on road traffic safety. The mean driving speed during free flow conditions as well as the speed differences between driving lanes were not affected by CCC.
- Time to collision (TTC) related indicators showed that CCC resulted in a reduction (up to 60%) of potentially dangerous conflicts (TTC < 4s), but that the number of

safety critical conflicts (TTC < 1,5s) increased (up to 10%) as the penetration level of CCC increases. These effects mainly occurred at times and locations at which congestion was reduced. It could be possible that safety critical conflicts occur more often in case of high V/C ratios (i.e. flow volume near capacity) that result in an unstable traffic flow but no congestion.

- CCC did not affect lane change patterns at the examined stretch of road.

On the basis of the described research and the limitations of this research, no hard conclusion could be drawn about the effects of CCC on road traffic safety but certainly some interesting new insights were obtained. Based on this research, CCC is expected to influence road traffic safety through changes in traffic flow and through effects that are related to the driver. For the case study area, both positive and negative traffic flow related safety effects were found. However, the number of safety critical conflicts seemed to increase as the penetration level of CCC increases. We recommend to further investigate road safety effects in more detail before implementing CCC and to gain knowledge how to improve the safety effects of next generations of the CCC system. Further research should in the first place aim at gaining more understanding of driver related effects of CCC. Moreover, we recommend to investigate traffic flow related effects on multiple locations and for different time periods. In the investigation of effect on traffic flow, it would be beneficial to also include traffic safety indicators**.**

7. Will drivers use Connected Cruise Control?

The effectiveness of the Connected Cruise Control system is dependent on drivers compliance with the advice. If the driver is not able and willing to follow that advice, the system will have no effect. This chapter describes the aspects that can influence a driver's willingness and ability to comply to CCC advice.

Human Factors considerations for designing tactical driver advice

The CCC system provides advice on the tactical driving level, with advice about headway, speed and lane use. The timing of the individual in-car advice is very important. A high frequency of advice may enable a better response to changing traffic conditions with the highest potential for increasing throughput, while at the same time this increases workload and decreases acceptance. A low frequency does not overload the driver and may increase acceptance. In the CCC project the advice frequency has been defined as maximum once per minute.

The sensory modality at which the advice is presented determines the distraction and workload that the system causes for the user. By nature, driving is primarily a visual task. In order to avoid overload and visual distraction, the CCC advice is given in the form of an audio message. The visual modality is used to present cues for the motivation of an advice in the form of a limited set of pre-defined icons that provide information about the upcoming traffic situation. This motivation is also presented by the audio warning preceding the advice. As a result, the driver can process the advice without having to read actual text. Figure 20 gives an impression of the CCC human-machine interface. The status indicator switches from red to green as the system is functional (e.g. has contact with the back office, ready to give advice). As the motivation for this advice example, a grey warning sign for a traffic jam has been chosen to indicate that the traffic jam is over. When the replay button is pushed, the audio message is played again.

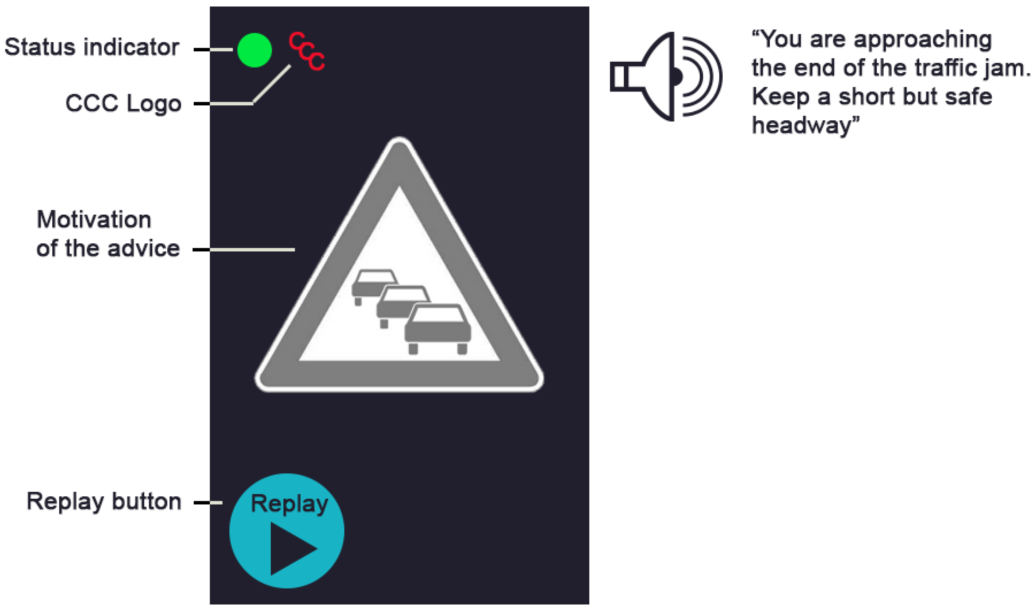

Figure 20: An impression of the CCC human-machine interface giving a "short headway" advice.

Restricting the advice to the auditory modality implies that the moment at which the driver receives the information is determined by the system (system-paced). Voice messages allow the system to provide instructions for more complex tactical driving manoeuvres with the possibility to keep the eyes on the road. However, as a result drivers may fail to memorize the long messages. Therefore advice messages have been chosen to convey the intention of the advice in as few words as possible, but with a sufficient amount of information in order to make it self-explaining.

An advice needs to be presented timely. This means that the whole advice message needs to be provided before the action is required and should allow for sufficient time to interpret the information and carry out the advice before the advice has lost its relevance. This reduces the feasibility of short termed advice (e.g. “change lanes now”). For the CCC project, advices have been chosen that can remain relevant over a longer period of time within a changing traffic environment.

The advice is sent to CCC equipped vehicles in a standardized form that conveys a behavioural goal of what should be done. However, phrasing of the advice can have a substantial impact on the way how the advice is complied to. In the course of the project different formulations have been tested in order to obtain those formulations that lead to driver behaviour closely resembling the behavioural goal.

Driver-need for tactical driver advice and willingness to comply

A user survey has been conducted in order to assess the need for tactical driver advice among road users. Participants of the survey were asked to state their irritation with other drivers’ speed, headway and lane use related behaviour. The ten most annoying tactical driver behaviours as indicated by the survey are shown in table 3. This list provides a guideline for the areas where a support of tactical driver behaviour is needed.

Table 3: Driver annoyance with tactical driver behaviour

#	Description
1	Late, aggressive merging at a lane drop, on-ramp or off-ramp
2	Driving left without a cause
3	Tailgating
4	Excessive lane changing in congestion
5	Hindrance with merging at a lane drop, on-ramp or off-ramp
6	Incorrect or no use of the indicator
7	Early merging at a lane drop, motorway entrance or exit
8	Merging with speed differences at a lane drop, on-ramp or off-ramp
9	Long-lasting passing manoeuvres
10	Deviating from the general speed limit

Participants were also asked to name factors that would influence their likelihood to adopt the system. Foremost was a perceivable beneficial effect of the system. Answers also indicate that drivers are aware of the interdependence between road users when it comes to traffic flow improvement. Participants remarked that they would base their use of the system on the condition that a substantial number of other drivers use the system as well. However, later experiments in the CCC project indicated that drivers are not able to determine whether vehicles around them are guided by CCC instructions or not, based on observation of vehicle behaviour. This inability can turn out beneficial for system acceptance, when drivers perceive the penetration rate of the system higher than it really is, or detrimental for acceptance when, due to lack of observable system-effect, penetration rate may be perceived lower than it really is.

A lack of trust in the system has been identified as a factor that in particular can influence the rejection of CCC. Furthermore, participants would reject a system whose instructions were in conflict with their own opinion about the optimal behaviour.

Drivers ability to follow specific headway advice

During the project several forms of specific and less specific headway advice have been tested. Specific headway advice was provided in terms of following distance (meters) or time headway (seconds). Results from a CCC driving simulator experiment show that drivers were able to follow the instructions of the headway advice to some extent, both for instructed time headway and distance headways. The differences in the chosen headway, provided in seconds or in meters were small. However, drivers were not able to follow the exact headways that were advised. This was the case for the various speeds and in various advised headway sizes. When the advised headway was 1 second, this lead to the lowest error in comparison to an advised headway of 1.5 or 2 seconds. The higher the speed, the higher the error. This was the case for absolute errors, that included headways that were too low and too high. These results were replicated on a real road with similar effects.

In order to see if some form of support would help drivers in choosing a more accurate headway (closer to the advised headway), half of the participants received a tone if the right headway was achieved. This helped drivers, but mainly in the higher speeds (where errors were the highest). For lower speeds this did not result in any additional positive effect.

The drivers inability to follow specific headway advice with great accuracy reduced the merit of a specific formulation in favour of a less specific formulation. Less specific headway advice was provided in terms of an absolute distance (i.e. a short but safe headway) or in terms of an advised manoeuvre (i.e. leave room for merging vehicles). Subsequent experiments with the less specific “short but safe” headway advice in real traffic did not lead to a change in time headway. However, it should be noted that the mean time headway at the time of advice was around 1 second and that this may already be perceived as short but save by participants.

Effect of CCC advice on driver behaviour

The effect of lane change advice, speed advice and headway advice on driver behaviour was tested in a driving simulator during a lane drop, an on-ramp, a weaving section and a straight motorway scenario.

In general, lane change advice led to lane changes taking place in a smaller region just after the advice was given. However, for the weaving section no difference was found between lane changes with or without a CCC lane change advice. This was due to the fact that even without the advice, road users have the tendency to change lanes as soon as the uninterrupted road marking ends. It is not possible for the CCC system to advice lane changes before this location. To reduce the number of vehicles that changes lanes directly at the end of the road markings CCC might advise drivers to delay their lane change in these situations.

It was hypothesized that lane change advice may cause unsafe situations and irritation as drivers may change lanes in order to comply to the advice and therefore accept smaller gaps. However, from the experiment no change in accepted gap size between advised and unadvised lane changes could be observed.

During a lane change, the absolute difference in speed (i.e. higher or lower) to vehicles on the target lane reduced following the “adjust speed before lane change” advice. However, the positive effect of the advice was stronger in scenarios where participants had to reduce their speed to adapt to the other lane. Unexpectedly, when there was a time interval of one minute between the speed advice and the lane change advice, the ‘adjust speed to the right lane’ advice tended to result in a premature lane change to the right.

The advice to leave room for merging vehicles led to a reduction of speed in a lane drop, an on-ramp and a straight motorway scenario. In the lane drop and on-ramp scenario it also lead to an increase in headway. After vehicles had merged in these scenarios headways were not further increased by the participants.

There were no observations of an increase of driver’s mental workload by adhering to CCC advice in comparison to unadvised driving.

The results indicate that in most cases CCC advice can lead to the intended adjustment of driving behaviour. However, sometimes these changes in driver behaviour can trigger subsequent behaviour that was not intended, as seen with the premature lane changes after the ‘adjust speed’ advice. Furthermore, close consideration should be paid not only to the way how the CCC advice is followed in different scenarios but also to the interaction between advised and non-advised vehicles. As for example in the weaving scenario. Knowing that, in this situation, other drivers are naturally changing lanes as soon as it becomes possible can help to adjust the advice to better distribute lane changes over a wider area.

Corrected mental model of the system

In order to improve traffic flow the goal is to have larger proportion of CCC equipped vehicles on the road. The effectiveness and the benefit of the system arises from the coordination of a larger group of CCC equipped vehicles. However, each driver receives an individual advice. Judging from this advice, drivers are unable to perceive themselves as part of that larger strategy. Without further information about the collective approach, that is applied by CCC, any advice that a driver receives will be evaluated from his/her individual standpoint. Yet, in itself the advice may not convey its beneficial effect for the traffic situation to the individual driver. It has been argued that the problem may be solved by improving a drivers mental model of how CCC works and the strategy it uses to improve traffic flow. An experiment has shown that increased knowledge of the working model of CCC can increase the perceived usefulness and satisfaction with the system despite a lack of additional information about the reason for a particular advice.

Drivers' evaluation of real time information and advice in real traffic

If correct, real time information on the traffic condition (in the form of a prediction of the upcoming traffic situation as a motivation to the advice) was valued favourable by participants. Drivers also requested information on situations where no advice was given, explicitly indicating the experienced usefulness of such a system.

Often, participants attempted to validate the information that they received from the system. However, using the information that was available (through perception of the situation at the time of the advice) participants found themselves often unable to verify the correctness of the information. The actual correctness of the advice was therefore often derived from observation of the actual development of the situation. Imperfections in the prediction of traffic developments reduced trust in the system and led to a devaluation of the information. For example, occasionally drivers received information about an imminent end of a traffic jam with an advice to keep a short but safe headway. However, shortly after the advice was given they perceived again a slowing down of traffic. The next time that they received the same advice they remarked that they were hesitant to follow the advice of a short headway as they were afraid of sudden reduction in speed of the vehicle in front.

The largest threat to the compliance of an advice was participants' experience with a particular situation in combination with his/her expected individual utility from the advice compared to an alternative behaviour. When the advice was perceived to lead to an unfavourable outcome (where unfavourable was usually considered unfavourable for the participant) the chance of compliance was reduced. In situations where the outcome of an advice was not directly predictable, or the participant had no preferred alternative behaviour, the likelihood for compliance increased.

During the on-road evaluation of the system certain forms of advice were repeatedly given in similar locations. For example, participants approaching a lane drop on the middle lane were advised to make room for merging vehicles or change lanes to the right. Participants that had passed the congestion that was caused by a lane drop usually received an advice to keep a short headway in order to accelerate more efficiently out of the congested area. Furthermore participants request for advice showed where they had expected information or an advice that was not given. For example, when drivers ended up in congestion, they usually remarked that the system should have informed them about the upcoming congestion and should have advised them to reduce their speed. These expectations provide valuable information to further adjust the advice to the needs of the driver.

Drivers also requested warnings about approaching congestion or, while they were standing in a traffic jam, an estimation of its size and approximate waiting time. These are situations where CCC in its current form would remain silent as it cannot improve the situation with an advice. By issuing warnings and information that are uncoupled from the actual advice, CCC might create an individual benefit by providing real-time traffic information.

8. Outlook

Result

The Connected Cruise Control system is the first of its kind system, aiming to give tactical driving advice on headway, speed and lane choice based on downstream traffic flow conditions. The project has been successful in developing and demonstrating the Connected Cruise Control system in real traffic. The backbone of the overall system implementation was an in-vehicle telematics platform with GPRS communication with a back office system collecting and processing traffic data. The traffic flow prediction and driver advice module were successfully implemented as well as the Human Machine Interface in the vehicle. Drivers highly appreciate the spoken CCC advice and traffic flow simulations showed potential delay reductions up to some 30%.

Opportunities

As a next step, the CCC system and its supporting telematic infrastructure are ready for application at a larger scale, as part of existing factory-fitted or retro-fitted navigation systems and as a smartphone app. This will enable to collect experience on the user acceptance and response and the operation of the algorithms at a larger scale, both in terms of CCC fleet size as well as road network scale on the basis of real floating car data as well loop detector data.

In the Netherlands, lane drops as considered in the test area are estimated to contribute to 10% of all traffic jams and 1.9 Million hours vehicle delay (14% of the total vehicle delay) (Jonkers et al., 2013). According to the results of the simulations, Connected Cruise Control could reduce up to 30% of this vehicle delay. In addition, the acceleration advice Connected Cruise Control may further contribute to a reduction of any traffic jam.

Interestingly, the supporting telematics infrastructure of CCC allows for extension of the CCC functionality towards green waves, road works and incidents and fuel efficient driving.

Challenges

However, there are also some challenges to be addressed. These challenges concern localization, positioning and timing of the advice, in particular obtaining lane level positioning and localization with commercially feasible system requirements, reducing latencies in the data communication and using floating car data from more vehicles.

Although the CCC project was primarily aimed at improving traffic efficiency, preliminary research into the impacts on traffic safety remained inconclusive. Further research is therefore recommended into the potential impacts on traffic safety and strategies to even use CCC to improve traffic safety, e.g., by taking traffic safety into account on the advice strategy.

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