EXPERIMENTAL EVALUATION OF A
COMMUNICATION BASED COOPERATIVE
DRIVING ALGORITHM

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ABSTRACT
This paper presents a cooperative longitudinal control system for a cluster of vehicles using an
environment sensor (radar) and vehicle-to-vehicle communication. The controller computes a de-
sired acceleration that is realized by a lower-level control loop to obtain a smooth and safe traffic
flow in a string of vehicles. State information from the host vehicle and preceding vehicles, ob-
tained by environment sensing and vehicle-to-vehicle communication, are fused to obtain reliable
signals. The system is evaluated on functional performance using test drives.

KEYWORDS
vehicle-to-vehicle communication, sensor fusion, longitudinal vehicle control, cooperative adap-
tive cruise control, test drives.

INTRODUCTION
With the increasing demand for safer passenger vehicles, the development of Advanced Driver
Assistance (ADA) systems is a major research topic in the automotive industry. An ADA system
is a vehicle control system that uses environment sensors (e.g. radar, laser, vision) to improve
driving comfort and traffic safety by assisting the driver in recognizing and reacting to potentially
dangerous traffic situations. Examples of ADA systems that have already been introduced to the
market are driver warning systems that actively warn the driver of a potential danger, such as lane
departure warning and forward collision warning systems.

Another widely available system since the 1990’s is adaptive cruise control (ACC), which provides
a more active support to the driver. ACC is a comfort system that maintains a set cruising velocity,
unless an environment sensor detects a slower vehicle ahead. The ACC then controls the vehicle
to follow the slower vehicle at a safe distance $\Delta d$, see figure 1. Since the available literature on
ACC systems is vast, the interested reader is referred to [5] for further details. Some drawbacks of
ACC are mentioned though:

- ACC systems have a maximum range of about 200 m, which is insufficient for warning about
  traffic jams or other potential danger further ahead.
- False and missed target detections can occur when driving in curves or when other vehicles
  or road infrastructure are blocking the line-of-sight of the sensor.
- In addition, the sensor signals can be unreliable due to multi-path reflections, weather con-
ditions and sensor noise.

Therefore, ACC could be greatly enhanced when the field-of-view of the sensorial platform is
extended to include information from other preceding vehicles. This can be achieved by imple-
menting a communication system between vehicles, so-called Vehicle-to-Vehicle Communication
(VVC). Current research is focussed on extending ACC systems to cooperative adaptive cruise control (CACC) systems [2], where the inter-vehicle distance is accurately estimated using VVC and environment sensors. The advantage of CACC is that it has an increased control bandwidth and reliability with respect to ACC. However, CACC is only operational with regard to the directly preceding vehicles that are sensed by the environment sensors. The ACC will therefore not directly respond to other preceding vehicles further ahead.

Another possibility of VVC is a cooperative collision warning and avoidance system, which has been the topic of research within several EU projects, such as the former CARTALK project [3] and WILLWARN [4]. An advantage of these systems is that they can receive collision warnings and traffic information from vehicles further ahead, instead of only the directly preceding vehicle.

The objective of this paper is to present a new ADA system that combines the ACC function with a cooperative system that looks multiple vehicles ahead, based on GPS navigation, environment sensing and VVC. This ADA system, called Integrated full-Range Speed Assistant (IRSA), has been developed within the internal TNO SUMMITS program. This paper focuses on the control of a system of three vehicles, whereas other activities within SUMMITS focus on the effects on a traffic flow level [6]. Test drives are used in order to validate the system’s safety.

DEMONSTRATOR VEHICLES

This section presents the hardware and sensor fusion algorithms of the demonstrator vehicles that are used in this research.

Hardware implementation

The demonstrator vehicles are Smarts, small 2-seaters, depicted in figure 2. The Smarts are instrumented with electronically controlled actuators: throttle, brake, gearbox and steering. In addition, they are equipped with several sensors: differential GPS (dGPS), accelerometers, wheel speed sensors and a gyroscope. Both Smarts are also equipped with an environment sensor (radar or lidar).

In addition, the Smarts are equipped with wireless local area network (WLAN) modules such that they can receive and transmit information to other vehicles within a range of several hundreds of meters, depending on the environmental conditions. The signal processing and control algorithms, which are described below, are implemented on a real-time Linux based PC/104 computer system.

On-board filtering

Cooperative vehicle control requires accurate and reliable knowledge of the state of the host vehicle and target vehicles. However, the information from only one sensor is usually not reliable and
Figure 2 – The Smart vehicles.

Table 1 – Smart instrumentation.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Signal</th>
<th>Noise variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>dGPS</td>
<td>x\text{gps}</td>
<td>10m²</td>
</tr>
<tr>
<td></td>
<td>y\text{gps}</td>
<td>10m²</td>
</tr>
<tr>
<td></td>
<td>ψ\text{gps}</td>
<td>0.4rad²</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>a\text{long}</td>
<td>0.02(m/s²)²</td>
</tr>
<tr>
<td></td>
<td>a\text{lat}</td>
<td>0.03(m/s²)²</td>
</tr>
<tr>
<td>Gyroscope</td>
<td>ψ</td>
<td>1.2·10⁻⁶ (rad/s)²</td>
</tr>
<tr>
<td>Wheel encoders</td>
<td>v_{ij}</td>
<td>3·10⁻⁴(m/s)²</td>
</tr>
<tr>
<td>Steer angle encoder</td>
<td>δ_i</td>
<td>1·10⁻⁴(m/s)²</td>
</tr>
<tr>
<td>Radar</td>
<td>x_{r,\text{radar}}</td>
<td>0.03 m²</td>
</tr>
<tr>
<td></td>
<td>v_{r,\text{radar}}</td>
<td>0.01(m/s)²</td>
</tr>
<tr>
<td></td>
<td>ψ_{r,\text{radar}}</td>
<td>0.004rad²</td>
</tr>
</tbody>
</table>

accurate enough for longitudinal vehicle control. For example, dGPS alone is not sufficient for real-time position information, because of the low update rate (1 Hz) and the inaccuracy. Therefore, information from multiple sensors is fused using an Extended Kalman Filter (EKF). This EKF is based on a non-linear dynamic model of the vehicle motion, taking into account that the sensor measurements are perturbed by Gaussian white noise, as indicated in table 1. In this way all desired vehicle states can be obtained with sufficient update rate and accuracy. In [1] we have elaborated on the integration of the different signals for the vehicle state. In this paper, focus is put on the estimation of the inter-vehicle states.

Estimation of the relative motion

For the development of a cooperative driving system, information on the relative motion between vehicles is required, characterized by the distance \(x_i\), relative speed \(v_i\), and relative angle \(ψ_i\). In the demonstrator vehicles two methods for obtaining information on the relative motion between vehicles are available: using direct sensor measurements or with VVC. For obtaining relative motion information via VVC a kinematic model is used, as shown in Figure 3. In this figure, \(x_i\), \(y_i\), and \(ψ_i\) represent the vehicle position and orientation, where the subscript indicates the \(i\)-th vehicle; \(v_{x,i}\) and \(v_{y,i}\) are the longitudinal and lateral velocity at the vehicle center of gravity (COG), respectively; \(L_1\) is the distance between the COG and the rear end of vehicle 1; \(L_2\) is the distance
between the COG and the front end of vehicle 2. The kinematic equations for the relative motion are given by:

\[
x_r = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} - (L_1 + L_2) \tag{1}
\]

\[
\psi_r = \psi_2 - \theta \tag{2}
\]

\[
v_r = v_{x,1} - v_{x,2} \cos(\psi_r) - v_{y,2} \sin(\psi_r) \tag{3}
\]

where \(\theta\) can be computed with:

\[
\theta = \arctan\frac{y_1 - y_2}{x_1 - x_2} \tag{4}
\]

Using the kinematic equations from (1)–(4), the local states computed by the on-board EKF, which are available to vehicles in the vicinity via VVC, can be used to compute the relative motion states \(x_{r,\text{comm}}, v_{r,\text{comm}}\) and \(\psi_{r,\text{comm}}\). In addition, the same states are also available directly from radar or lidar measurements, denoted by \(x_{r,\text{radar}}, v_{r,\text{radar}}\) and \(\psi_{r,\text{radar}}\). In order to provide an accurate and reliable estimation, the relative motion information from both sources is combined. Figure 4 shows this scheme to obtain the estimated states \(x_{r,\text{est}}, v_{r,\text{est}}\) and \(\psi_{r,\text{est}}\). In the fault management block discrepancies between the two signals are detected and the corrected signal is used as the fault-free estimate. Figures 5(a) and 5(b) depict the distance and relative velocity during a test run with the two Smarts. In each of these two figures, the values obtained from radar measurements, the values computed with the relative motion model using VVC and the fault-free values are depicted.

**Figure 3** – Model of the relative motion between two vehicles.

**Figure 4** – Fault management system for estimation of the relative motion.
In these figures it can be seen that the fault-free signal is much more reliable than the two separate sensor signals.

**LONGITUDINAL CONTROL FOR COOPERATIVE DRIVING**

In this section, an algorithm for ACC is described and extended to cooperative driving in a cluster of vehicles. Two hierarchical levels can be distinguished in the control architecture. The outer loop (high level controller) consists of the cooperative longitudinal controller that computes a reference acceleration $a_d$ based on the sensor information. The inner loop (low level controller) consists of an acceleration controller that tracks an acceleration command $a_d$ from the outer loop as good as possible. The advantage of this configuration is that these two loops can be designed separately, reducing the overall complexity of the design. Furthermore, this structure can also be well motivated from the relation between driver and vehicle: the inner loop corresponds to the vehicle dynamics and the outer loop corresponds to the driving behavior. The outer loop is therefore vehicle independent, to a certain extend. A schematic overview of the control structure is given in figure 6. In this figure, the block ‘fault-free states’ denotes the system described in the previous section.

**Longitudinal Control Algorithm**

The ACC longitudinal control problem consists of two vehicles, as shown in figure 1. In velocity control mode, the ACC operates as a conventional cruise control, where the desired acceleration
\(a_d\) is given by a proportional controller according to:

\[
a_d = k_{cc}(v_{cc} - v_2), \quad k_{cc} > 0
\]

where \(v_{cc}\) is the set-point for the velocity.

For distance control, the desired acceleration \(a_d\) for vehicle 2 is usually given by feedback control of the distance separation error \(e_x = x_t - x_d\) and its derivative \(e_v = \dot{e}_x = v_t - v_d\):

\[
a_d = k_2 e_v + k_1 e_x, \quad k_1, k_2 > 0
\]

to obtain a desired acceleration \(a_d\) that controls both \(e_x\) and \(v_t\) to zero. In order to achieve a natural following behavior, the desired clearance is chosen as \(x_d = \max(v_2 t_h, s_0)\) and the feedback gains are calculated by nonlinear functions \(k_1 = f_1(v_2, x_t, t_h, s_0)\) and \(k_2 = f_2(v_2, t_h)\), where \(s_0\) is a distance safety margin and \(t_h\) is the driver-selected time gap. The non-linear functions \(f_1\) and \(f_2\) are chosen such that the behavior of a normal driver is mimicked, aiming to increase the system acceptance by drivers.

**Algorithm for Cooperative Driving**

A control law for cooperative driving can be similar to (6). However, the main advantage of cooperative driving is that there is more information available, such as the acceleration of the preceding vehicle. Using VVC, the acceleration of the lead vehicle (which is difficult to estimate with only an environment sensor) can be communicated to the following vehicle. With information on the acceleration \(a_t\), as well as more reliable estimates for the range and range rate, the ACC control law (6) can be modified to:

\[
a_d = k_3 a_t + k_2 e_v + k_1 e_x, \quad k_1, k_2, k_3 > 0
\]

where \(k_3\) is a non-constant feedforward gain. The availability of an acceleration signal in the feedback control law provides an opportunity to react faster to emergency braking of a preceding vehicle.

Because the reference acceleration from (7) only considers a single vehicle, a method has been developed to consider more vehicles in front, which is the aim of cooperative driving. A conceptual overview of cooperative driving with the Smart vehicles using VVC is shown in figure 7. The idea is that vehicle 3 in figure 7 should not only keep a headway of \(x_{d,2}\) to vehicle 2, but it should also keep a headway of \(x_{d,1} + l_v + x_{d,2}\) to vehicle 1. Based on this idea, the algorithm computes a desired acceleration \(a_{d,i}\) for each preceding vehicle \(i\), according to (7). The desired acceleration \(a_d\) to be sent to the vehicle’s lower-level controller is then calculated by taking the minimum of all \(a_{d,i}\) for all \(n-1\) preceding vehicles:

\[
a_d = \min(a_{d,n-1}, \ldots, a_{d,1})
\]

**Figure 7 – Overview of a cluster of three vehicles, using vehicle-to-vehicle communication.**
Equation (8) implies that the host vehicle will respond to the preceding vehicle that produces the lowest \( a_{d,i} \). However this may result in a very conservative controller. Therefore, the accelerations \( a_{d,i} \) for vehicles further ahead (so for \( i \leq n-2 \)) have to cross a threshold value \( a_{\min} \) or \( a_{\max} \), before they are used in (8), according to:

\[
a_{d,i} = \begin{cases} 
0, & \text{if } a_{\min} < a_{d,i} < a_{\max} \\
a_{d,i}, & \text{otherwise}
\end{cases}, \quad i \leq n-2
\]  

(9)

**Design of the inner control loop**

Contrary to the outer loop the design of the inner control loop is specific for each vehicle. The acceleration (inner loop) controller has been realized by using a feedforward control based on the vehicle model that includes engine, brake and gearbox dynamics. In addition, feedback of the acceleration signal and a PI controller realizes \( a_{d} \) accurately.

**FIRST EVALUATION OF THE IRSA COOPERATIVE DRIVING SYSTEM**

Test drives have been performed to perform a first evaluation of the developed IRSA algorithms. In the following, test results obtained with a cluster of three vehicles, comprising both Smarts and a lead vehicle, are reported. The lead vehicle – equipped with VVC – is driven by a driver and the two Smarts behind it are automatically controlled by the developed algorithms.

The goal of these experiments is to analyze the functionality (both headway determination and longitudinal controller) of the whole cooperative system for different manoeuvres at different velocities. Two test scenarios have been defined:

- **Cut-in**: starting from a steady state situation at 50 km/hr, the lead vehicle suddenly strongly decelerates, for instance due to yet another vehicle closely cutting-in in front of the lead vehicle.

- **Traffic jam approach**: starting from a steady state situation, both Smarts approach the lead vehicle at about 50 km/hr. The lead vehicle is standing still. This resembles a traffic jam approach.

In order to compare automatic cooperative driving with manual driving, the same two scenarios have also been tested without the help of the cooperative driving system. The drivers were specifically instructed to keep the same time headway as the automatic system would. It should be noted that although the drivers were instructed to drive without exaggerated attention to the front vehicle, they knew that the front vehicle would brake sooner or later. This knowledge obviously influences the reaction time significantly.

In figure 8 a comparison between manual driving and automatic driving on the basis of the accelerations of the three vehicles is made for the cut-in scenario. It can be seen that for manual driving it takes the two following vehicles 1.1 s and 1.9 s, respectively to react on the front vehicle, while for automatic driving both following vehicles start braking 0.9 s later than the front vehicle. Especially the rear vehicle has to brake very hard (-6 m/s\(^2\)) for manual driving in order to avoid a collision. With automatic cooperative driving the rear vehicle can stop at the right distance by applying only mild decelerations (maximum of -3 m/s\(^2\)).

**CONCLUSIONS**

A cooperative vehicle control system has been presented that uses state estimation of individual vehicles combined with vehicle-to-vehicle communication and measurements from an environment sensor, thus extending the horizon of the follower vehicles beyond the directly preceding vehicle.
In addition, this redundancy allows for fault-tolerant longitudinal control in case of sensor faults or communication outage. The conclusion that could be drawn from test drives is that with CACC the maximum deceleration of the rear vehicle (and the middle vehicle to a lesser extent) was much less than in case of manual driving. A reason for this, is that CACC drastically reduces the reaction time on sudden maneuvers. As a consequence, not only comfort but also safety is improved.

REFERENCES


