**Preprints of the 19th World Congress**
**The International Federation of Automatic Control**
**Cape Town, South Africa. August 24-29, 2014**

# Design of adaptive cruise control for road vehicles using topographic and traffic information ⋆

**Péter Gáspár** * **Balázs Németh** **

* *Institute for Computer Science and Control, Hungarian Academy of Sciences, MTA-BME Control Engineering Research Group, Hungary; Fax: +36-14667503; Phone: +36-12796171; E-mail: gaspar@sztaki.hu*
** *Institute for Computer Science and Control, Hungarian Academy of Sciences, Hungary; Kende u. 13-17, H-1111 Budapest, Hungary; Phone: +36-12796173; E-mail: bnemeth@sztaki.hu*

**Abstract:** The paper proposes the design of the speed of road vehicles, which minimizes control energy and fuel consumption while keeping travelling time and, moreover, considers the local traffic information to avoid conflicts in congestions. Topographic data and speed limits on the road are incorporated into the design of fuel efficient operation of the vehicle. Since the biased consideration of fuel consumption may lead to the reduction of speed, the traffic flow in the surroundings of the vehicle may be impaired. Thus, the information about the local traffic is an important factor considering the wider transportation system. In the paper the energy-efficient predicted cruise control strategy is presented, which is able to adapt to the motion of the surrounding vehicles. In this way a balance between the designed speed and the flow of the local traffic can be guaranteed.

*Keywords:* adaptive cruise control, look-ahead control, road preview, traffic information, optimization.

## 1. INTRODUCTION AND MOTIVATION

The development of an energy-efficient operation strategy has been in the focus of research and development centers, suppliers and manufacturers. The purpose of the energy-efficient operation is to design the speed of road vehicles, in which several factors are taken into consideration such as energy requirement, fuel consumption, road slopes, emissions and travelling time. Consequently, the look-ahead control methods are based on multi-objective optimization criteria. The advantage of these methods is that they can be connected to the adaptive cruise control strategy.

Several papers have been published in these topics. The optimization problem was handled by using a receding (sliding) horizon control approach in Hellström et al. (2010); Passenberg et al. (2009). In Hellström et al. (2009) the predicted control approach was evaluated in real experiments, based on the combination of GPS signals and information about the road geometry. Németh and Gáspár (2013a) proposed the design of speed for road vehicles based on road inclinations, speed limits, a preceding vehicle in the lane and traveling time. Saerens et al. (2013) proposed an eco-cruise control strategy, in which the multi-criteria optimization between journey time and fuel consumption was converted into a constrained fuel optimization task. Several scenarios were presented by Rakha et al. (2006) for the relationship between travel time, energy and the emission of the vehicle. In Asadi and Vahidi (2011) a predictive cruise control was proposed, which was able to consider upcoming traffic signal information to improve fuel economy and reduce traveling time. The algorithm used radar and traffic signals to optimize traveling speed.

In the case of hybrid electric vehicles the road prediction is important to optimize battery recovery. The efficiency of terrain preview was demonstrated using simulation examples in Zhang et al. (2010). Ambühl and Guzzella (2009) presented the predictive reference signal generator method to maximize recuperated energy using the topographic profile of the future road segments and the corresponding average traveling speeds. In van Keulen et al. (2010) a speed optimization method was detailed for heavy electric trucks. In the method the shape of the vehicle speed profile at a road segment was predefined and its parameters were determined during a nonlinear constrained optimization process. Schakel et al. (2010) analysed the effects of cooperated adaptive cruise control on the mixed traffic flow. During the cooperation between vehicles the shockwaves in traffic can be damped efficiently. In this way the individually-controlled vehicles are able to guarantee a coordinated motion and improve traffic flow.

The look-ahead control is also motivated by the design of a platoon control system. A cooperative control strategy based on preview information, which initiates the change in speed for all vehicles in the platoon, was proposed by

⋆ The research has been conducted as part of the project TÁMOP-4.2.2.A-11/1/KONV-2012-0012: Basic research for the development of hybrid and electric vehicles. The Project is supported by the Hungarian Government and co-financed by the European Social Fund.

Alam et al. (2013). The method of look-ahead control was extended to the design of the common speed of the vehicles in the platoon in Németh and Gáspár (2013b). The goal was to determine the common speed at which the speeds of the members are as close as possible to their own optimal speed.

Although the efficiency of terrain preview consideration in cruise control has been proposed in several publications, a smaller emphasis has been placed on traffic flow impair caused by speed reduction. In most papers, the traffic flow in the environment of the controlled vehicle is influenced during the journey. However, in the methods listed above, the motion of the other vehicles on the road is not taken into consideration. For example, the driver of the look-ahead vehicle is able to create a balance between energy/fuel saving and journey time according to his own priorities. However, other drivers on the road have different priorities, which can lead to conflict, e.g. fast vehicles are held up by vehicles traveling in a fuel efficient fashion.

The goal of the research is to design an optimal look-ahead control strategy which is able to adapt to the motion of the surrounding vehicles. In this way a balance between fuel economy and the speed of vehicles on the road can be guaranteed. The combination of the look-ahead concept and the congestion problem leads to a complex multi-criteria optimization task.

The paper is organized as follows. The principles of the applied look-ahead concept are briefly presented in Section 2. In Section 3 the interaction of look-ahead strategy with the follower vehicle motion is formulated using optimization criteria. Section 4 presents the architecture of the design method incorporating the optimization processes. The efficiency of the method is illustrated through a simulation example in Section 5. Finally the contributions of the paper are summarized in Section 6.

## 2. PRINCIPLES OF LOOK-AHEAD CONTROL

In the section the principles of the consideration of road conditions in speed profile design are briefly summarized. A detailed description of the method is found in Németh and Gáspár (2013a).

The road ahead of the vehicle is divided unevenly, which is consistent with the topography of the road. In the method the vehicle is assumed to be traveling in a segment from the initial point to the first division point. The speed at the initial point is predefined and it is called original speed. The aim is to calculate the so-called modified speed at the same initial point at which the reference speed of the first point can be reached by using a constant longitudinal force. This thought can be extended to the next segments and division points. In the case of $n$ number of segments and $n+1$ number of points as Figure 1 shows, $n$ equations are formulated between the first and the end points. It is assumed that the acceleration of the vehicle may change in the different intervals, but within an interval the acceleration is constant.

The motion of the vehicle is described using simple kinematic equations: $s_1 = \dot{\xi}_0(\dot{\xi}_1 - \dot{\xi}_0)/\ddot{\xi} + (\dot{\xi}_1 - \dot{\xi}_0)^2/2/\ddot{\xi}$, where $\dot{\xi}_0$ is the speed of the vehicle at the initial point,

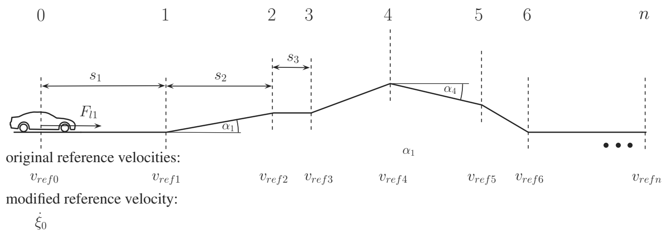



Fig. 1. Division of road

$\dot{\xi}_1$ is the speed of vehicle at the first point and $s_1$ is the distance between these points. $F_{di}$ disturbances considered in vehicle dynamics are divided in two groups: The first group is force resistance from the road slope $F_{di,r}$, which can be considered as a measured signal during the road slope measurement. The second group $F_{di,o}$ contains all of the other resistances such as rolling resistance and aerodynamic forces. The unmeasured resistances $F_{di,o}$ can be approximated by the square of $\xi_0$ for the road sections as $F_{di,o} = A + T\dot{\xi}_0^2$, where $A$ and $T$ are constant vehicle parameters.

Based on the previous kinematic modeling framework the speed of the vehicle at point $i \in \{1, 2, ..., n\}$ is written as: $\dot{\xi}_i^2 = \dot{\xi}_0^2 + \frac{2}{m}\sum_{j=1}^{i} s_j\left(F_{lj} - F_{dj}\right)$. Similarly, the speed of the vehicle is formulated in the next $n$ section points. Using this principle, a speed-chain which contains the required speeds along the way of the vehicle is constructed. At the calculation of the control force it is assumed that additional longitudinal forces $F_{li}$, $i \in \{2, ..., n\}$ will not affect the next sections. It means that always the actual $F_{l1}$ control force must be computed and applied as momentary actuation. Thus, the predicted speed of the $i^{th}$ section point is the following:

$$\dot{\xi}_i^2 = \dot{\xi}_0^2 + \frac{2}{m}(s_1 F_{l1} - \sum_{j=1}^{i} s_j F_{dj}) \tag{1}$$

When the vehicle arrives at a speed limit, the vehicle speed $\dot{\xi}_i$ must reach this limit $v_{ref,i}$. Therefore the following aim must be achieved for all of the section points: $\dot{\xi}_i^2 \to v_{ref,i}^2$. This defined condition is rearranged using the kinematical relationship and the form of disturbance. Consequently, the equations of the vehicle speeds at the section points are calculated in the following way:

$$\dot{\xi}_0^2 \to v_{ref,0}^2, \tag{2}$$

$$\dot{\xi}_0^2 + \frac{2}{m}s_1 F_{l1} - \frac{2}{m}s_1 F_{d1,o} \to v_{ref,i}^2 + \frac{2}{m}\sum_{j=1}^{i} s_j F_{dj,r}, \tag{3}$$

where $i \in \{1, 2, ..., n\}$. Since the vehicle travels in traffic and it may happen that it catches up with a preceding vehicle. Due to the risk of collision it is necessary to consider the speed of the preceding vehicle $v_{lead}$:

$$\dot{\xi}_0^2 \to v_{lead}^2 \tag{4}$$

In the next step prediction weights $\gamma_1, \gamma_2, ..., \gamma_n$ are applied to (3). They represent the priority of the $i^{th}$ condition. Two additional prediction weights are applied: $Q$ and $W$ based on (2) and (4), respectively. The weights must sum up to one, i.e.

$$\gamma_1 + \gamma_2 + ... + \gamma_n + Q + W = 1. \tag{5}$$

While the prediction weights $\gamma_i$ represent the rate of the road conditions, weight $Q$ has an essential role: it determines the tracking requirement of the current reference speed $v_{ref,0}$. By increasing $Q$ the momentary speed becomes more important while road conditions become less important. For example when $Q = 1$ the control task is simplified to a cruise control problem without any road conditions. By making an appropriate selection of the weights the importance of the road condition is taken into consideration. When equivalent weights are used the road conditions are considered with the same importance, i.e., $Q = \gamma_i$, $i \in \{1, 2, ..., n\}$. $W$ represents the tracking of the speed $v_{lead}$. When $W = 1$ only the tracking of the preceding vehicle is carried out. The determination of $W$ is based on the distance from the preceding vehicle to minimize collision risk, see Németh and Gáspár (2013a).

By using (3) and (4) and taking the weights into consideration the following formula is yielded:

$$\dot{\xi}_0^2 + \frac{2}{m} s_1 (1 - Q - W) F_{l1} - \frac{2}{m} s_1 (1 - Q - W) F_{d1,o} = \vartheta \tag{6}$$

where value $\vartheta$ depends on the road slopes, the reference speeds and the weights

$$\vartheta = W v_{lead}^2 + Q v_{ref,0}^2 + \sum_{i=1}^{n} \gamma_i v_{ref,i}^2 + \frac{2}{m} \sum_{i=1}^{n} s_i F_{di,r} \sum_{j=i}^{n} \gamma_j . \tag{7}$$

In order to take the road conditions into consideration in the control design (6) is applied as a performance of the controlled system. Finally, a speed tracking problem is deduced, whose reference signal contains the predicted road information (road slopes, speed limits), such as:

$$\dot{\xi}_0 \to \lambda \tag{8}$$

where parameter $\lambda$ is calculated in the following way based on the designed $\vartheta$:

$$\lambda = \sqrt{\vartheta - 2 s_1 (1 - Q - W)(\ddot{\xi}_0 + g sin\alpha)} \tag{9}$$

### *2.1 Optimization of the vehicle cruise control*

Equation (6) shows that the modified speed $\dot{\xi}_0$ depends on the prediction weights ($W$, $Q$ and $\gamma_i$). By choosing these values the effects of road conditions can be tuned. The design of the vehicle speed profile poses two optimization problems, which are written in the following forms:

*Optimization 1:* The longitudinal control force must be minimized, i.e., $|F_{l1}| \to$ min. Instead, in practice the $F_{l1}^2 \to$ min optimization is used because of the simpler numerical computation. It leads to a quadratic optimization problem, which is written in the following form using (6):

$$\bar{F}_{l1}^2 = (\beta_0(\bar{Q}) + \beta_1(\bar{Q})\bar{\gamma}_1 + \ldots + \beta_n(\bar{Q})\bar{\gamma}_n)^2 \to \min \tag{10}$$

with the following constrains $0 \le \bar{Q}, \bar{\gamma}_i \le 1$ and $\bar{Q} + \sum \bar{\gamma}_i = 1 - W$. This task is nonlinear because of the weights. At fixed $Q$ weights the optimization task is solved by the transformation of the quadratic form into the linear programming using the simplex algorithm.

*Optimization 2:* The difference between momentary speed and modified speed must be minimized, i.e., $|v_{ref,0} - \dot{\xi}_0| \to$ min. In this case the optimal solution can be determined easily, since the vehicle tracks the predefined speed if the road conditions are not considered. Consequently, the optimal solution is achieved by selecting the weights in the following way: $\breve{Q} = 1 - W$ and $\breve{\gamma}_i = 0, i \in [1, n]$.

The two optimization criteria lead to different optimal solutions. In the first criterion the road inclinations and speed limits are taken into consideration by using appropriately chosen weights $\bar{Q}, \bar{\gamma}_i$. At the same time the second criterion is optimal if the information is ignored. In the latter case the weights are noted by $\breve{Q}, \breve{\gamma}_i$.

A balance between the performances must be achieved, which is based on a tuning of the weights. Several methods can be applied in this task. In the proposed method two further performance weights, i.e., $R_1$ and $R_2$, are introduced. Performance weight $R_1$ ($0 \le R_1 \le 1$) is related to the importance of the minimization of the longitudinal control force $F_{l1}$ (Optimization 1) while performance weight $R_2$ ($0 \le R_2 \le 1$) is related to the minimization of $|v_{ref,0} - \dot{\xi}_0|$ (Optimization 2). There is a constraint according to the performance weights $R_1 + R_2 = 1$. Thus the performance weights, which guarantee a balance between optimizations tasks, are calculated in the following expressions:

$$Q = R_1 \bar{Q} + R_2 \breve{Q} = 1 - W - R_1(1 - \bar{Q} - W) \tag{11a}$$

$$\gamma_i = R_1 \bar{\gamma}_i + R_2 \breve{\gamma}_i = R_1 \bar{\gamma}_i \tag{11b}$$

with $i \in \{1, .., n\}$. The equations show that prediction weights depend on $R_1$ linearly. Based on the calculated performance weights the modified speed can be determined by using (9).

## 3. CONSIDERATION OF THE MOTION OF THE FOLLOWER VEHICLE IN SPEED DESIGN

Normally the driver sets weight $R_1$ based on his goals and requirements, thus he creates a balance between energy saving and travelling time. However, a vehicle preferring energy saving may be in conflict with other vehicles preferring cruising at the speed limit. Thus, an energy-efficient vehicle may decelerate the other vehicles on the road. Preferring weight $R_1$ leads to a non-optimal motion for the traffic globally. In this section a weight calculation method which guarantees a balance between the energy-efficient speed profile and the flow of the local traffic is proposed for $R_1$. Thus, the motion of the vehicle using the look-ahead control and the motion of the follower vehicle are analyzed.

### *3.1 Predicting the speed of the vehicle using look-ahead control*

The speed prediction of the vehicle using look-ahead control is based on (3). In the following the unmeasured resistances $F_{di,0}$ is considered. Based on (7) the expression of $\vartheta$ can be rewritten as:

$$\begin{aligned}\vartheta =& W v_{lead}^2 + (1 - W) v_{ref,0}^2 - R_1 (1 - \bar{Q} - W) v_{ref,0}^2 + \\ &+ R_1 \sum_{i=1}^{n} \bar{\gamma}_i v_{ref,i}^2 + R_1 \Big(\frac{2}{m} \sum_{i=1}^{n} s_i F_{di,r} \sum_{j=i}^{n} \bar{\gamma}_j\Big) = \\ =& R_1 \bar{\vartheta} + v_{ref,0}^2 (1 - R_1)(1 - W)\end{aligned} \tag{12}$$

where $\bar{\vartheta}$ contains the value of $\vartheta$ calculated with energy-efficient prediction weights $\bar{Q}, \bar{\gamma}_i$.

From (8) the reference speed $\lambda$ is calculated based on the predicted road information. It shows that through $Q$ and $\vartheta$ weight $R_1$ plays an important role in the calculation of the reference speed. Moreover, the predicted values of the weights $\gamma_i$ also depend on $R_1$, see (11). From (6) and (7) the square of the reference speed $\dot{\xi}$ is calculated in the following form:

$$\begin{aligned}\lambda^2 =& R_1\bar{\vartheta} + v_{ref,0}^2(1-R_1)(1-W)+\\ &- 2s_1R_1\left(1-\bar{Q}-W\right)(\ddot{\xi}_0 + gsin\alpha)\\ =& R_1\left(\bar{\vartheta} - 2s_1(1-\bar{Q}-W\right) + v_{ref,0}^2(1-R_1)(1-W)\\ =& R_1\bar{\lambda}^2 + v_{ref,0}^2(1-R_1)(1-W) \end{aligned} \tag{13}$$

From (3) and (13) the predicted estimated speed of the vehicle at section point $n$ is

$$\begin{aligned}\dot{\xi}_n^2 &= \dot{\xi}_0^2 + \frac{2}{m}s_1F_{l1} - \frac{2}{m}s_1F_{d1,o} - \frac{2}{m}\sum_{i=1}^{n} s_iF_{di,r}\\ &= \lambda^2(1-\frac{2}{m}s_1T) + \frac{2}{m}s_1F_{l1} - \frac{2}{m}s_1A - \frac{2}{m}\sum_{i=1}^{n} s_iF_{di,r}\\ &= R_1\mathcal{N}_1 + \mathcal{N}_2 \end{aligned} \tag{14}$$

According to (14) the predicted speed at point $n$ is independent of $v_{ref,n}$ . For example when $R_1 = 0$ the predicted speed at point $n$ must be $v_{ref,n}$. However, using (14), the value $\dot{\xi}_i$ depends only on the momentary speed limit $v_{ref,0}$, while future speeds $v_{ref,i}$ do not influence it.

Based on (14) the defined reference speed at section point $n$ must be modified in the following way:

$$\dot{\xi}_n^2 = (R_1\mathcal{N}_1 + \mathcal{N}_2)R_1 + (1-R_1)v_{ref,n}^2 \tag{15}$$

Consequently, the estimated speed at section point $n$ is

$$\dot{\xi}_n = \sqrt{(R_1\mathcal{N}_1 + \mathcal{N}_2)R_1 + (1-R_1)v_{ref,n}^2} \tag{16}$$

which depends on the weight $R_1$. In the formula $\mathcal{N}_1$ is independent of the section points ahead, while $\mathcal{N}_2$ contains the road grade information of each section.

### 3.2 Predicting the motion of the follower vehicle

Hereinafter it is necessary to determine the criterion of the safety distance between the vehicle using the look-ahead control and the follower vehicle. It requires the estimation of the motion prediction of the follower vehicle. The controlled vehicle moves from point $\xi_0$ to $\xi_1$, whose distance is $s_1$ while the traveling time is $\Delta t_1$. Meanwhile the follower vehicle moves from point $\eta_0$ to $\eta_1$.

In the optimization method it is assumed that although the acceleration of the vehicle may change in the different intervals, within an interval acceleration is constant. Thus, the traveling time in the first interval is expressed as $\Delta t_1 = 2s_1/(\dot{\xi}_1+\lambda)$, where $\lambda$ and $\dot{\xi}_1$ are from equations (13) and (15), respectively. The traveling time between points $\xi_1$ and $\xi_2$ is expressed similarly as $\Delta t_2 = 2s_2/(\dot{\xi}_2 + \dot{\xi}_1)$.

In the estimation of the follower vehicle several assumptions are considered. First, the preceding vehicle has information about the speed and acceleration of the follower vehicle ($\dot{\eta}_0$, $\ddot{\eta}_0$) and the momentary distance between the vehicles $e_0$. Second, the follower vehicle accelerates evenly until it reaches the speed limit. When the follower vehicle reaches the speed limit $v_{ref,j}$ it does not accelerate further, thus in the oncoming sections the predicted speeds of the vehicle are $v_{ref,j}, \ldots, v_{ref,n}$. Note that the optimal speed of the preceding vehicle is continuously re-designed, thus the motion of the follower vehicle must be predicted.

In the following, based on the information $\dot{\eta}_0$, $\ddot{\eta}_0$, $e_0$ the motion of this vehicle must be calculated in every sections in which the traveling time is $\Delta t_i$, $i = \{1 \ldots n\}$. Until the follower vehicle reaches the speed limit, i.e., $k < j$, the distance of the vehicle is the following:

$$\eta_k = \frac{\ddot{\eta}_0}{2}\left(\sum_{i=1}^{k}\Delta t_i\right)^2 + \dot{\eta}_0\sum_{i=1}^{k}(\Delta t_i) \tag{17}$$

where $k \in [1, ..., j-1]$. When the follower vehicle reaches the speed limit at section $j$ the equation is the following:

$$\eta_l = \frac{\ddot{\eta}_0}{2}\left(\sum_{i=1}^{j-1}\Delta t_i\right)^2 + \dot{\eta}_0\sum_{i=1}^{j-1}(\Delta t_i) + \sum_{i=j}^{l}(v_{ref,i}\Delta t_i) \tag{18}$$

where $l \in [j, ..., n]$. After this section the speed of the follower vehicle is considered $v_{ref,l}$.

### 3.3 Safety distance criterion

Now the safety distance between the vehicle using the look-ahead control and the follower vehicle must be guaranteed. The safety distance $s_{safety}$ is assumed to be predefined. The controlled vehicle intends to use the energy-efficient predicted cruise control, while the follower vehicle aims to keep the speed limit. Thus, the look-ahead control strategy is modified in such a way that the motion of the follower vehicle is taken into consideration. A possible method is to modify weight $R_1$ during the journey and create a balance between the designed speed and the required speed of the follower vehicle. The aim of this section is to develop a method for the re-design of weight $R_1$.

The criterion of the safety distance is based on the motion of the vehicles. During the journey in every section the distance between the two vehicles must be guaranteed by the following inequalities:

$$\xi_i + e_0 - \eta_i \geq s_{safety}, \quad i \in \{1, 2, .., n\} \tag{19}$$

where $\xi_i$ is the predicted displacement of the controlled vehicle, $e_0$ is the momentary distance between the vehicles and $\eta_i$ is the predicted displacement of the follower vehicle. It is necessary to find the maximum of weight $R_1$, which guarantees the inequality constraints (19). Note that an increase in $R_1$ induces longer journey time. Therefore $R_1$ can be limited by the driver using a predefined bound $R_{1,max}$.

The optimization criterion of the safety cruising is formulated as follows:

$$\max_{[0;R_{1,max}]} R_1 \tag{20}$$

such that the following conditions are satisfied:

$$\sum_{i=1}^{j} s_i + e_0 - \eta_j - s_{safety} \geq 0, \quad j \in \{1, ..., n\} \tag{21}$$

In these inequalities $\eta_j$ depends on weight $R_1$. The result of the optimization $R_{1,opt}$ is used in the calculation of the prediction weights $Q$ and $\gamma_i$. Based on the prediction weights and equation (9) the reference speed $\lambda$ of the controlled vehicle is computed. The optimization procedure (20) is performed in each step, thus weight $R_1$ is rewritten continuously according to the current local traffic information.

## 4. ARCHITECTURE OF THE SPEED PROFILE DESIGN METHOD

In practice the solution of the optimization processes (10), (20) may require a great deal of computation effort. However, the constrained quadratic optimization problem (10) is reformulated to a linear programming task. In this way the computation of $\bar{Q}, \bar{\gamma}_i$ requires less time. In the case of the other optimization (20) the solution of the previous computation step $R_{1,old}$ is applied as initial value.

The new solution $R_{1,new}$ is searched in the interval

$$[\max(R_{1,old} - \alpha, 0), \min(R_{1,old} + \alpha, R_{1,max})]$$

with $n = 10$ points and $\alpha = 0.1$. Note that $R_{1,max}$ is set by the driver. Its default value is $R_{1,max} = 1$. Both optimization (10) and (20) are solved with sample time $0.005s$. The purpose of this procedure is to guarantee that the complexity of the optimization method is reduced and, thus, the method can be applied in practice.

Figure 2 illustrates that the vehicle receives information about the motion of preceding vehicle (distance and speed) and the follower vehicle (distance, speed, acceleration). Moreover, the road inclination $\alpha_i$ and speed limit $v_{ref,i}$ data are also known. Since the route of the vehicle is considered as known, the loading of this information requires the measurement of the current position, e.g. using GPS.

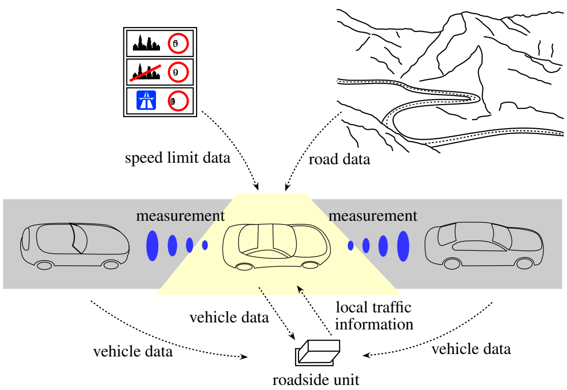



Fig. 2. Communication and information flow

Ebnre and Hermann (2001) provided a survey of the future communication possibilities in automotive and traffic control. Nuevo et al. (2010) presented a computer vision-based approach to tracking surrounding vehicles and estimating their trajectories. An extension of adaptive cruise control with traffic information considering vehicle-to-roadside and vehicle-to-vehicle communication was proposed in Kesting et al. (2007). Festag et al. (2008) combined vehicle-to-vehicle communication and vehicle-to-roadside sensor communication to prevent accidents and assist investigations.

## 5. SIMULATION RESULTS

In this section the proposed speed design method is demonstrated through a simulation example using high-complexity vehicle dynamic software CarSim. In the scenario a maneuver is considered, in which a controlled vehicle with the presented method overtakes slower preceding vehicles on the highway (*controlled*). The overtaking maneuver is carried out by using an energy-efficient method. At the same time another vehicle equipped by an conventional adaptive cruise control drives onto the highway and accelerates to reach the speed limit and also begins an overtaking maneuver (*follower*). Thus, there is a conflict between the vehicles caused by the decreased distance between the *controlled* and *follower* vehicles during their maneuver. In the following example the efficiency of conflict handling based on the proposed control strategy is presented.

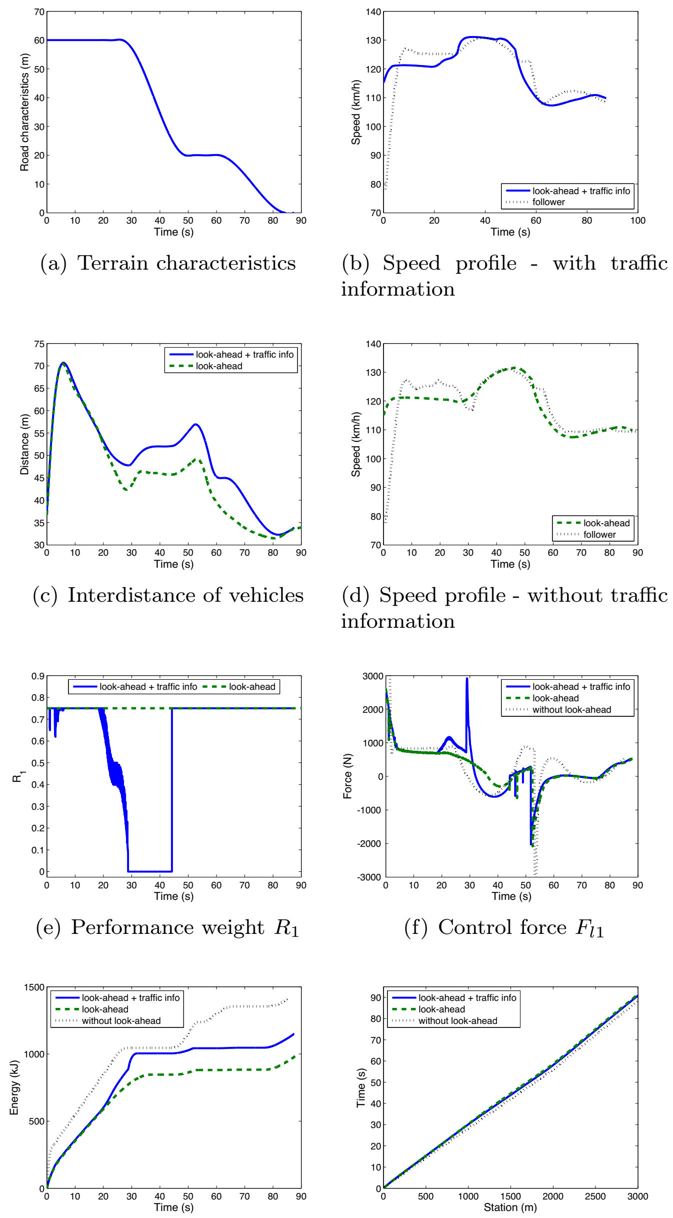
The terrain characteristics of the road are illustrated in Figure 3(a). This road contains downhill sections, whose inclinations are 5% and 3%. The energy-efficient cruising of the vehicle requires the reduction of vehicle speed before the downhill sections. The speed limit on the highway is $130km/h$, which is reduced to $110km/h$ before the second inclination. The speed profiles of the *controlled* vehicle with a control strategy and the *follower* vehicle are shown in Figure 3(b).

The *follower* vehicle drives onto the busy highway at $80km/h$ and accelerates dynamically to reach the speed limit $130km/h$. The *controlled* vehicle is moving at approximately $110km/h$, since the acceleration effect of the predicted slope is considered. In the example $R_{1,max} = 0.75$ is set by the driver. Note that this is the tuning parameter. Consequently, the performance weight changes in the interval $0 \leq R_1 \leq R_{1,max}$ method.

At the beginning of the simulation performance weight $R_1$ is chosen 0.75, therefore the control force $F_{l1}$ is minimized, see Figures 3(e) and 3(f). However, the distance between the vehicles is reduced, which may cause a conflict. In order to hold the safety distance $s_{safety}$ the priority of $R_1$ must be reduced, see Figure 3(f). At 45 *sec* the overtaking maneuver of the *controlled* vehicle is finished, thus $R_1$ is reset to 0.75. The reduction of $R_1$ results in the increase of vehicle speed in the first simulation case during the increase of $R_2$. Therefore $F_{l1}$ is increased, see Figure 3(f). It leads to higher fuel consumption, since it is necessary to avoid a hazardous conflict.

In the other simulation the motion of *follower* is not considered by the *controlled* vehicle. Figure 3(d) shows the speed profile of the vehicles. Since the *controlled* vehicle considers mainly the predicted terrain characteristics $R_1 = 0.75$, the interdistance is decreased continuously, see Figure 3(c). Although in this case $F_{l1}$ is minimized during the entire road, the motion of the *controlled* vehicle caused a traffic conflict. The *follower* vehicle must significantly reduce its speed in its lane, which is unacceptable, see Figure 3(d). Besides, the interdistance is decreased below $s_{safety}$, which is also dangerous on the highway.

The energy consumption of the *controlled* vehicle using the presented strategy is shown in Figure 3(g). It is compared with a vehicle without traffic information and another vehicle without look-ahead strategy. As long as $R_1 = 0.75$, the energy consumption of the vehicle with traffic information and the vehicle without that is the same, see Figure 3(e). When $R_1$ is reduced control energy consumption increases significantly, because terrain characteristics are less considered. Thus, the tendency of energy consumption




(a) Terrain characteristics
(b) Speed profile - with traffic information
(c) Interdistance of vehicles
(d) Speed profile - without traffic information
(e) Performance weight $R_1$
(f) Control force $F_{l1}$
(g) Control energy consumption
(h) Traveling time

Fig. 3. Simulation results of the overtaking maneuver

is close to the vehicle without look-ahead strategy. In the presented simulation scenario the energy consumption of the presented method is approximately 75% of an uncontrolled vehicle. Figure 3(h) illustrates the traveling time values of the vehicles. Although energy saving of the look-ahead strategy is considerable, the traveling time of the vehicle increases. Without look-ahead strategy the journey time is 87 *sec*, while the vehicle with look-ahead strategy considering traffic information travels 3000 $m$ in 90 *sec*. The time increase of the proposed strategy is 3%. The results show that the energy consumption is significantly higher than the time lost.

## 6. CONCLUSIONS

The paper has proposed a speed design method which can be built in the adaptive cruise control strategy. In the method several factors such as energy requirement, road slopes, traveling time, road disturbances and speed limits have been taken into consideration and a multi-objective optimization procedure has been formed. Since the vehicle is part of the transportation system, this energy-efficient cruise control strategy has been coordinated with the motion of the surrounding vehicles. In the design method performance weight $R_1$ has been tuned in order to keep the safety distance between vehicles. The simulation example has shown that by considering the predicted speed of the other vehicles conflict events can be avoided.

## REFERENCES

Alam, A., Martensson, J., and Johansson, K. (2013). Look-ahead cruise control for heavy duty vehicle platooning. *Proc. 16th IEEE Annual Conference on Intelligent Transportation Systems, The Hague.*

Ambühl, D. and Guzzella, L. (2009). Predictive reference signal generator for hybrid electric vehicles. *Vehicular Technology, IEEE Transactions on*, 58(9), 4730–4740.

Asadi, B. and Vahidi, A. (2011). Predictive cruise control: Utilizing upcoming traffic signal information for improving fuel economy and reducing trip time. *Control Systems Technology, IEEE Transactions on*, 19(3), 707–714.

Ebnre, A. and Hermann, R. (2001). A self-organized radio network for automotive applications. *8th World Congress on Intelligent Transportation Systems, Sydney, Australia.*

Festag, A., Hessler, A., Baldessari, R., Le, L., Zhang, W., and Westhoff, D. (2008). Vehicle-to-vehicle and road-side sensor communication for enhanced road safety. *15th World Congress on Intelligent Transport Systems.*

Hellström, E., Åslund, J., and Nielsen, L. (2010). Horizon length and fuel equivalents for fuel-optimal look-ahead control. *Advances in Automotive Control, Munich*, 1–6.

Hellström, E., Ivarsson, M., Åslund, J., and Nielsen, L. (2009). Look-ahead control for heavy trucks to minimize trip time and fuel consumption. *Control Engineering Practice*, 17(2), 245–254.

Kesting, A., Treiber, M., Schönhof, M., and Helbing, D. (2007). Extending adaptive cruise control to adaptive driving strategies. *Transportation Research Record*, 2000, 16–24.

Nuevo, J., Parra, I., Sjoberg, J., and Bergasa, L. (2010). Estimating surrounding vehicles' pose using computer vision. In *13th IEEE Conf. on Intelligent Transportation Systems*, 1863–1868.

Németh, B. and Gáspár, P. (2013a). Design of vehicle cruise control using road inclinations. *International Journal of Vehicle Autonomous Systems*, 11(4), 313–333.

Németh, B. and Gáspár, P. (2013b). Optimised speed profile design of a vehicle platoon considering road inclinations. *IET Intelligent Transport Systems.*

Passenberg, B., Kock, P., and Stursberg, O. (2009). Combined time and fuel optimal driving of trucks based on a hybrid model. *European Control Conference, Budapest*, 1–6.

Rakha, H., El-Shawarby, I., Arafeh, M., and Dion, F. (2006). Estimating path travel-time reliability. *IEEE Intelligent Transportation Systems Conference, Toronto, Canada*, 236–241.

Saerens, B., Rakha, H., Diehl, M., and den Bulck, E.V. (2013). A methodology for assessing eco-cruise control for passenger vehicles. *Transportation Research Part D*, 19, 20–27.

Schakel, W., Van Arem, B., and Netten, B. (2010). Effects of cooperative adaptive cruise control on traffic flow stability. In *13th IEEE Conf. on Intelligent Transportation Systems*, 759–764.

van Keulen, T., de Jager, B., Foster, D., and Steinbuch, M. (2010). Velocity trajectory optimization in hybrid electric trucks. In *American Control Conference*, 5074–5079.

Zhang, C., Vahidi, A., Pisu, P., Li, X., and Tennant, K. (2010). Role of terrain preview in energy management of hybrid electric vehicles. *IEEE Transactions on Vehicular Technology*, 59(3), 1139–1147.