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COMMUNICATION BASED LONGITUDINAL VEHICLE CONTROL USING AN EXTENDED KALMAN FILTER

**R. Hallouzi * V. Verdult * H. Hellendoorn * P.L.J. Morsink **
J. Ploeg ****

** Delft Center for Systems and Control,
Delft University of Technology*

Mekelweg 2, 2628 CD Delft, The Netherlands

*** TNO Automotive, Advanced Chassis and Transport Systems
P.O. Box 6033, 2600 JA Delft, The Netherlands*

Abstract: This paper presents the design of a longitudinal controller for a cluster of vehicles with inter-vehicle communication (IVC). By applying IVC a smooth traffic flow can be realized. The proposed controller can actively control the throttle, the brake and the gears of the used vehicles in order to do so. The longitudinal controller uses two loops; the outer loop computes a desired acceleration, which the inner loop uses as a reference. The outer loop uses acceleration, velocity and position information from the own vehicle and preceding vehicles. These three states first have to be estimated from various sensors in the vehicle. An Extended Kalman Filter (EKF) has been used for fusing the signals from the different sensors. The used signals are available from DGPS and from inertial sensors on the test-vehicles. Real-life experiments with the proposed algorithm for a cluster of three vehicles will demonstrate the usefulness of the approach.

Keywords: Kalman filter, sensor fusion, sliding-mode control, throttle/brake control, longitudinal control, Co-operative driving.

1. INTRODUCTION

Different strategies have been proposed to address the problem of traffic congestion and passenger safety and comfort. Advanced Driver Assistance Systems (ADAS) are designed to decrease the workload of drivers. An example of such a system is a Stop & Go controller (Yamamura et al., 2001). This controller can automatically follow the preceding vehicle throughout the whole speed range of the vehicle by using distance sensors.

Although Stop & Go systems can reduce workload and increase safety and comfort, they do this by only regarding the direct predecessor. The application of IVC however can expand this functionality by taking into account more vehicles beyond the direct predecessor. This is known as Co-operative driving. For this application the distance to the predecessors (headway) has to be known. In this paper a method is proposed to determine the headway by IVC. An ac-

curate real-time estimation by each vehicle is required for this purpose. This position is communicated to the vehicles behind along with the velocity and acceleration, which are necessary for the longitudinal control algorithm. Using IVC for distance determination is a cost-efficient method because no distance sensor has to be used. Furthermore distance sensors used in production vehicles are only capable of determining the distance to the direct predecessor, while the distance to more than one predecessor is desired for Co-operative driving.

The Differential Global Position System (DGPS) has been used for providing the global position. DGPS only however is not sufficient for providing the position for real-time purposes because a DGPS update is received with 1Hz. For real-time control a higher frequency is needed, which can be achieved by using inertial sensors. Navigation systems using accelerometers or gyroscopes are known as Inertial Navigation

Systems (INS). These additional sensors have much higher update rates and can therefore be used to complement the DGPS signals. In this project signals from an accelerometer and an odometer are fused by using an EKF. The Kalman Filter (KF) is a well known method for fusing signals with different properties and for state estimation. In the automotive industry the Kalman Filter has been used by several researchers for state estimation. Examples hereof can be found in Carlson et al. (2002); Gustafson et al. (2001). Other applications of the KF can be found in autonomous vehicles and robots (Thrapp et al., 2001; Kiri and Buehler, 2002).

This paper is organized as follows: In section 2 the sensor fusion of the different sensors will be explained. Section 3 will focus on the design of the longitudinal control algorithm. Subsequently experimental results will be presented in section 4. Finally, in section 5 the conclusions will be given.

2. SENSOR FUSION AND STATE ESTIMATION

In order to allow Communication Based Longitudinal Control (CBLCL) some vehicle states have to be known. Because the desired states can not be directly measured from one sensor they have to be estimated from various sensors. A state estimator that has to be applied for real-time longitudinal vehicle control must be accurate, robust and provide the estimates in real-time with a high enough update rate. The estimator for our purpose has to interpolate the position of the vehicle by adopting inertial measurements when there are no signals available from the DGPS system, furthermore it has to estimate some other desired states. The used estimator is an Extended Kalman Filter (EKF) (Anderson and Moore, 1979), based on a non-linear kinematic model of the vehicle movements.

2.1 Measurement model

The signals that have been used for the EKF are the acceleration of the vehicles in longitudinal and lateral direction from a tri-axial accelerometer. Furthermore the velocity from an odometer has also been used. Although an odometer is generally not regarded as an inertial sensor, in this paper it is for the sake of simplicity. From DGPS the longitude, latitude and heading measurements are used in the filter. These signals have been incorporated in the following measurement equations

$$z_{xDGPS}(k) = x(k) - x_{lat}(k) + \nu_{xDGPS}(k) \quad (1)$$

$$z_{yDGPS}(k) = y(k) - y_{lat}(k) + \nu_{yDGPS}(k) \quad (2)$$

$$z_{hDGPS}(k) = \theta(k) - \theta_{lat}(k) + \nu_{hDGPS}(k) \quad (3)$$

$$z_{ax}(k) = a_{xB}(k) + b_x(k) + \nu_{ax}(k) \quad (4)$$

$$z_{ay}(k) = a_{yB}(k) + b_y(k) + \nu_{ay}(k) \quad (5)$$

$$z_{odo}(k) = \sqrt{v_{xN}^2(k) + v_{yN}^2(k)} + N(k)\delta_c + \nu_{odo}(k) \quad (6)$$

In these equations the raw measurements denoted by $z_x(k)$ are written as a function of the desired values and some extra terms. All the measurements are modelled with an extra noise input ($\nu_x(k)$). For the accelerometer ($z_{ax}(k)$, $z_{ay}(k)$) and the odometer ($z_{odo}(k)$) an extra offset has been specified. The offset of the odometer is due to the inaccuracy of the multiplication factor C_{odo} . This multiplication factor is used to calculate the velocity from the numerical derivative of the odometer. The error of this factor is defined by δ_c , $N(k)$ is the amount of pulses per second from the odometer. The terms $b_x(k)$ and $b_y(k)$ are due to the bias of the accelerometer signals. The $x_{lat}(k)$, $y_{lat}(k)$ and $\theta_{lat}(k)$ terms compensate for the latency of the DGPS (see section 2.3).

2.2 System model

The next step is to describe the system model by kinematic equations. In these equations the assumption has been made that the vehicle behaves as a point-mass. This approach is quite common for position estimation purposes (Wada et al., 2000). Furthermore two space frames have been used, these frames are the navigation frame and the base frame. The base frame is the frame that moves with the vehicle, the navigation frame is a fixed frame in which the positioning takes place. The kinematic equations now become:

$$x(k) = x(k-1) + Tv_{xN}(k-1) + w_x(k) \quad (7)$$

$$y(k) = y(k-1) + Tv_{yN}(k-1) + w_y(k) \quad (8)$$

$$v_{xN}(k) = v_{xN}(k-1) + T \cos(\theta(k-1))a_{xB}(k-1) - T \sin(\theta(k-1))a_{yB}(k-1) + w_{v_{xN}}(k) \quad (9)$$

$$v_{yN}(k) = v_{yN}(k-1) + T \sin(\theta(k-1))a_{xB}(k-1) + T \cos(\theta(k-1))a_{yB}(k-1) + w_{v_{yN}}(k) \quad (10)$$

$$\theta(k) = \theta(k-1) + T \frac{a_{yB}(k-1)}{v_{xB}(k-1)} + w_\theta(k) \quad (11)$$

$$a_{xB}(k) = a_{xB}(k-1) + w_{a_{xB}}(k) \quad (12)$$

$$a_{yB}(k) = a_{yB}(k-1) + w_{a_{yB}}(k) \quad (13)$$

$$b_x(k) = b_x(k-1) + w_{b_x}(k) \quad (14)$$

$$b_y(k) = b_y(k-1) + w_{b_y}(k) \quad (15)$$

$$\delta_c(k) = \delta_c(k-1) + w_{\delta_c}(k) \quad (16)$$

$$v_{xB}(k) = \cos(\theta(k-1))v_{xN}(k-1) + \sin(\theta(k-1))v_{yN}(k-1) + w_{v_{xB}}(k) \quad (17)$$

In the above equations T is the sample time, the subscript N means that the concerning quantity is represented in the navigation frame and the subscript B means that the concerning quantity is represented in the base frame. The first two states, $x(k)$ and $y(k)$, represent the absolute positions in the navigation frame and are a discrete-time integration of the velocities $v_{xN}(k)$ and $v_{yN}(k)$. $v_{xN}(k)$ and $v_{yN}(k)$ are the longitudinal and lateral velocity in the navigation frame, they are obtained by integrating the rotated

accelerations. A rotation of the accelerations is necessary because the accelerations measured directly from the sensors on the vehicle are in the base frame. $a_{xB}(k)$ and $a_{yB}(k)$ are respectively the longitudinal and lateral acceleration of the vehicle in the base-frame. The error states that have been used are $b_x(k)$, $b_y(k)$ and $\delta_c(k)$. The first two error states are the biases of the acceleration sensors. $\delta_c(k)$ is the error in C_{odo} . The last state $v_{xB}(k)$ is the longitudinal velocity in the base frame, which is necessary in eq. 11. where the heading $\theta(k)$ is calculated. The heading $\theta(k)$ is calculated by integrating the yaw rate $\dot{\psi}$ of the vehicle. It should be noted that by adopting the relation in equation 11 for a vehicle it is assumed that there is no body slip angle and that the vehicle is represented as a point-mass.

2.3 Latency compensation

A fundamental limitation of the DGPS system is the delay with which the data becomes available in the vehicle. This delay is called *latency*. Since the data from the INS is obtained in real-time, the latency of the DGPS can introduce severe inaccuracies when it is not compensated. For this project a method for compensating this latency has been developed that does not require a re-estimation sequence of the EKF for the period the latency.

The EKF estimates the states based on the real-time INS data. The estimated states necessary for the latency compensation algorithm (x -position, y -position and heading) are buffered for L seconds (L is the length of the latency). When a DGPS update is received, it is known that this update represents data from L seconds ago and not real-time data. Ideally a re-estimation sequence of the whole EKF of L seconds in the past should take place in order to correct the estimation with the DGPS data correctly. For real-time purposes however this re-estimation sequence is not possible because the EKF keeps on estimating the states in real-time and can therefore not wait until a whole re-estimation has taken place. Instead a method is used where a DGPS update is used without re-estimating the whole state for L seconds. In this method the assumption has been made that the same sequence of states is estimated by the EKF that does not use the DGPS measurements as the EKF that uses the DGPS measurements for the period from $(1 - L)$ seconds before the update to the moment of the update. This assumption can be motivated by the fact that the DGPS data is only important in a small period during and after the update. By making this assumption the previously buffered data from the DGPS/INS filter can be subtracted from the DGPS update. In this way the estimated states are the real-time states predicted from the last DGPS-update. The DGPS observations can now be written as in equations 1,2 and 3. A graphical representation of this update process can be found in figure 1. Let x_0 be the estimation of a certain state at a certain time instant t_0 . Each time instant (t_1 , t_2 etc.) when the DGPS update arrives a

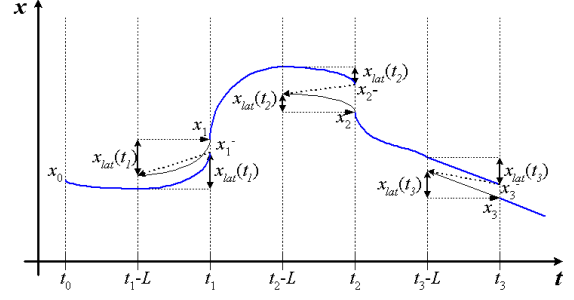


Fig. 1. Latency compensation

correction represented by the dotted line takes place in the past (L seconds ago) and a new state (x_1 , x_2 etc.) is calculated by adding the difference of the previously buffered data over L seconds. The distance $x_{lat}(t_n)$ in the figure representing this difference can be expressed as $x_{lat}(t_n) = x(t_n)^- - x(t_n - L)$ for DGPS update n (in the figure $x(t_n)^-$ is shortened to x_n^-). In equations 1,2 and 3 this difference is represented by respectively $x_{lat}(k)$, $y_{lat}(k)$ and $\theta_{lat}(k)$. After the update the state estimation process continues with x_1 rather than x_1^- etc. The time elapsed between t_0 and t_1 is 1 s, which is the update time of DGPS. In this time the DGPS/INS filter makes 50 estimations. In the figure the blue lines describe the estimated state trajectory with latency compensation. The correctness of the proposed method is demonstrated in Hallouzi (2003).

2.4 Fusion strategy

Because DGPS does not have new data available at all the sample times the EKF is run, a fusion strategy has been designed. This strategy uses the measurement noises of the DGPS measurements of equations 1,2 and 3. If a DGPS measurement has just arrived it should be made more important than the inertial measurements in order to correct the estimates with the new DGPS measurements. This can be done by a low measurement covariance. If the DGPS measurements become older, the measurement covariances should grow in order to decrease the trust in these measurements. This has been done by the following equation:

$$U(k) = 1 + c \log(u(k) + 1) \quad (18)$$

$U(k)$ is the function used as measurement covariance for the three DGPS measurements, c is a tuning factor and $u(k)$ is the signal that determines how old (in samples) the last DGPS update was.

3. LONGITUDINAL CONTROL ALGORITHM

The estimated vehicle parameters by the EKF as described in the previous section are going to be used for longitudinal control of the vehicles in the demo-setup. For longitudinal control of a cluster of vehicles, two hierarchical levels can be used. By using two loops these two loops can be designed separately from each other. This has the advantage that a division of

the complexities that can occur during the design is made. Furthermore this approach has the advantage that a separation is made between two aspects that are really present in a driver-vehicle system (Persson et al., 1999). These two aspects are driver behaviour, which corresponds with the outer loop, and vehicle dynamics, which corresponds with the inner loop. The outer loop controller specifies the acceleration that the current vehicle must achieve. This acceleration is based on algorithms using information obtained by communication between vehicles. The inner loop controller must obey the acceleration set-point as fast as possible. An overview of the control structure is given in figure 2.

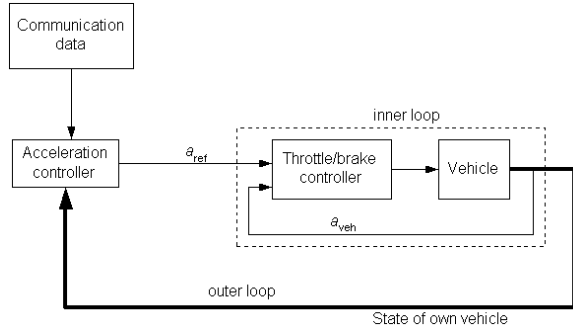


Fig. 2. Graphical representation of the control loops

3.1 Design of the outer control loop

The control objective of the outer loop is to keep a certain desired headway relative to the front vehicle. The outer loop however also has the aim to keep a desired headway relative to more vehicles beyond the direct predecessor. The desired headway uses a variable time headway h , defined by

$$h = h_0 - c\Delta v \quad (19)$$

where $h_0 > 0$ and $c > 0$ are constants and Δv is the relative velocity. This definition of the headway is quite intuitive (Yanakiev and Kanellakopoulos, 2001). A certain vehicle can maintain a time headway h_0 to its predecessor, while both are travelling at the same speed. If the preceding vehicle is travelling faster ($\Delta v > 0$), it is safe for the following vehicle to reduce the time headway until the velocities are equal again. However, if there is a slower preceding vehicle ($\Delta v < 0$), the time headway should be increased. The desired headway (separation) between the vehicles can be calculated by

$$d_{ref} = d_0 + hv_{veh} \quad (20)$$

where d_0 is the minimal headway between vehicles and v_{veh} is the vehicle velocity. The total acceleration value commanded to the lower level controller is calculated according to:

$$a_{ref} = c_1 a_{MND} + c_2 (d - d_{ref}) + c_3 (v_{i-1} - v_i) + c_4 (a_{i-1} - a_i) \quad (21)$$

c_1 - c_4 are positive constants and i is the index of the current vehicle, $i - 1$ is the index of the preceding vehicle etc. The tuning of the different parameters has to be done in a way that the outer loop behaviour corresponds with "real driver behaviour". In Bengtsson (2001) for example it is concluded from several research works that drivers tend to brake with a rather constant deceleration. Therefore the outer loop should also do so in order to give the driver a natural braking feel. This has been done by adding the term (Gietelink et al.)

$$a_{MND} = \frac{-\Delta v^2}{2(d - d_{ref} + dx)} \quad (22)$$

where dx is a positive term used to make sure that a_{MND} does not get too big in situations where $d \approx d_{ref}$ or even become negative when $d_{ref} > d$.

Because the reference acceleration from equation 21 only considers the front vehicle a method has been developed to also consider more vehicles in front, which is the aim of Co-operative driving. This method presented in Hallouzi (2003) does this by applying reference accelerations from more than one vehicle in front.

3.2 Design of the inner control loop

Contrary to the outer loop the design of the inner control loop is specific for each vehicle. In order to achieve a high level of control accuracy for the inner loop, the exact vehicle behaviour must be known. Furthermore the time scope of the design of a very detailed controller based on precise information of vehicle parameters is very large. Because these means were not available, the acceleration (inner loop) controller has been realized by using Sliding Mode Control (SMC) based on a simple vehicle model. SMC has been chosen because it is well known for its robustness to system modelling error and external disturbance (Slotine and Li, 1991). In the SMC the following vehicle model has been used:

$$ma + f = bu \quad (23)$$

where m is the mass of the vehicle, a is the acceleration, b is the control gain, u is the control input and f is the estimated longitudinal force acting in the opposite driving direction of the vehicle. The used sliding surface for the SMC S is:

$$S = \varepsilon + \lambda \int \dot{\varepsilon} \quad (24)$$

where $\varepsilon = a - a_{ref}$ is the control error and λ is the sliding gain. The control output of the SMC is given by:

$$u = \frac{(\frac{-\dot{\varepsilon}}{\lambda} + a_{ref})\hat{m} + \hat{f}}{\hat{b}} - \frac{k}{\hat{b}} \text{sat}(\frac{S}{\phi}) \quad (25)$$

where k is the discontinuous control gain and ϕ is the so-called boundary layer. These parameters can be used for tuning. The different model parameters from equation 23 in this control output are estimated values and are therefore denoted with a $\hat{\cdot}$ above them. A

discontinuous control term has been added in the right part of equation 25 for robustness. In this part of the equation the $\text{sat}(\cdot)$ function is used, which is defined as:

$$\text{sat}\left(\frac{S}{\phi}\right) = \begin{cases} \frac{S}{\phi}, & \text{if } \left|\frac{S}{\phi}\right| \leq 1 \\ \text{sgn}\left(\frac{S}{\phi}\right), & \text{if } \left|\frac{S}{\phi}\right| > 1 \end{cases} \quad (26)$$

$\text{sgn}(\cdot)$ is the function that returns the sign of the input parameter. The acceleration controller consists of two controllers, one that controls the throttle and another that controls the brakes. This choice has been made because the dynamics from throttle to acceleration are quite different from the dynamics from brake to acceleration. Because the controller should not apply the brake and the throttle at the same time, a switching law for brake and throttle control is used. In this law the residual acceleration is taken into account. The residual acceleration is the negative acceleration of the vehicle when the brake nor the throttle is applied. If a certain deceleration is desired then the brake will only be applied if this deceleration is smaller than the residual acceleration at the current velocity.

A problem that occurred in the inner loop acceleration controller is that during gear changes the throttle signal increased because of dips in the acceleration. This behaviour caused the automatic gearbox in the vehicles to shift down again during upshifts. Because of this double shifting it took even longer to change gears. A solution to this problem has been implemented by developing an own shift algorithm. Because of this algorithm the exact shift moments that were not known earlier were now known. These shift moments have been used to fix the throttle output during gear changes and to prevent the integrator in equation 24 from integrating during gear changes in order to prevent wind-up. In this way the influence of gear changes on the performance of the inner loop controller is drastically decreased.

4. EXPERIMENTAL RESULTS OF THE CONTROLLER

In order to display the functionality of the CBLC system at demonstrator-level a demo-setup with the required hardware has been built at TNO Automotive. The demo set-up, depicted in figure 3, consists of three test vehicles. All three vehicles can communicate via an infrared connection up to a distance of 300m. The front vehicle is a Peugeot 806 and the two vehicles behind it are Smarts. The Smarts have an electronically controlled automatic transmission and electronic throttle as standard equipment. The Peugeot is used as a lead vehicle on which the two Smarts that can be automatically controlled have to anticipate. The throttle and the gears of the Smarts can be controlled by the control computer. The braking system in the Smarts can also be controlled by the control computer by using a brake actuator that mechanically pulls the brake pedal. The control computer is in the



Fig. 3. Demo set-up

PC-104 format and the used operating system is Realtime Linux. Furthermore all vehicles are equipped with DGPS, accelerometers in longitudinal and lateral direction and a velocity sensor. The velocity sensor is actually a pulse counter (odometer) that is mounted at a wheel of the vehicles. The velocity can be computed from the counted pulses.

Firstly the position estimation from the EKF is evaluated separately. In figure 4 the estimated position of one of the vehicles is depicted together with the DGPS position for a certain trajectory driven with constant speed. It can be seen that the EKF position data is updated much more than the DGPS data (50Hz instead of 1Hz) and that between DGPS updates also a good position estimation occurs. Furthermore some small corrections of the position can be seen at the update moments due to small errors that occur when the EKF runs only on INS data.

Furthermore experiments have been conducted with the demo-setup to analyse the functionality of the whole CBLC system for different manoeuvres at different speeds. These experiments have been performed on a test track without other traffic that was placed at our disposal by the Dutch ministry of traffic. A scenario that has been tested was Stop & Go at different velocities. In this scenario the front vehicle drove from a stand-still position to a steady velocity of about 15m/s, after a while the front vehicle decelerated to stand-still again. The same routine was gone through once again, but the steady velocity was taken to be 17.5m/s the second time. Furthermore the second time the second time the front vehicle decelerated harder. The two following vehicles automatically followed the front vehicle.

In figure 5 the velocities of the three vehicles in this test scenario are depicted. In this figure it can be seen that the velocities of the three vehicles become equal at the two steady-situations and that the braking and accelerating manoeuvres of the front vehicle are followed by the two following vehicles. In figure 6 the accelerations of the three vehicles are depicted. In this figure it can be seen that the two following vehicles react instantaneously on decelerations of the front vehicle at 37s and 85s. This fast reaction is due to the Co-operative driving approach. Furthermore it can

be seen that the following vehicles have to brake less hard than the front vehicle because in clusters with a time headway it is allowed to keep a smaller headway at smaller velocities.

5. CONCLUSIONS

A Communication Based Longitudinal Control algorithm has been developed that uses state estimation of individual vehicles combined with inter-vehicle communication. For estimation of the desired states an Extended Kalman Filter has been used with DGPS as input. One of the estimated states was the position, which was used to determine the distance between vehicles. For this reason no distance sensor had to be used. The longitudinal controller was divided into two loops. The inner loop is an acceleration controller and the outer loop calculates the desired acceleration. From experiments it can be concluded that the CBLC system functions properly. The CBLC functionality shows a decrease in reaction times with respect to human drivers by early anticipation on more than one vehicle in front.

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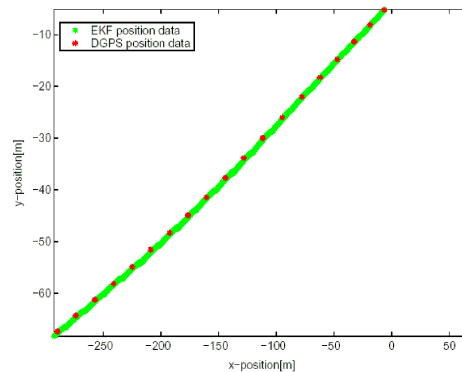


Fig. 4. Estimated and DGPS positions

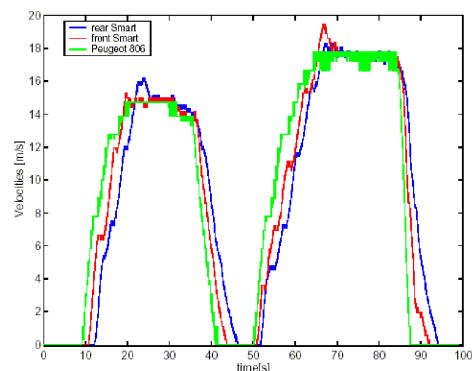


Fig. 5. Velocities of the three vehicles

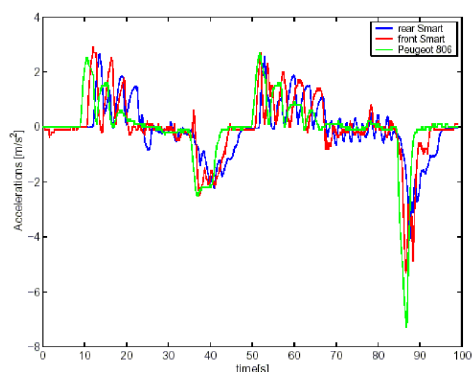


Fig. 6. Accelerations of the three vehicles