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Evaluation of methods to estimate vehicle location in Electronic Toll Collection Service with C-ITS*

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Abstract— **This paper aims to present our method to evaluate a vehicle location to perform Electronic Toll Collection transactions (ETC System) with Cooperative Intelligent Transport System (C-ITS) and to compare different model systems to evaluate the most reliable filter to have the vehicle location. We consider ITS components using the ITS-G5 technology with features specified by the European Telecommunication Standardization Institute (ETSI): RoadSide Unit (RSU) and On-Board Unit (OBU). The idea of the proposed algorithm takes advantage of the communications data. The method is inspired by the principle of Differential - GPS combined with Kalman Filtering or extended Kalman filtering applied to the GPS and CAN bus measurements performed on the RSU. The evaluation of the filter will be done according to the motion models chosen.**

I. Introduction

Many researches about intelligent transportation systems have been done and yet in process to enhance the transportation safety and to improve the related services. With this prospect of deployment of C-ITS in cars and on European roads, Sanef, a toll motorway operator in France, plans to offer a new mean to collect toll fees on highways for the connected vehicles. In fact, ETC service plays a critical role in the world of ITS: by contributing to effective collection of revenue needed to expand, and maintain road and highway infrastructure, as well as to operate them [1].

This paper is organized as follow: In Section II, the context of this research is addressed by presenting the state of art of the C-ITS and the ETC service. In section III, the approach to perform the ETC transaction with a reliable vehicle tracking is presented. In Section IV, simulation with the GPS and bus CAN measurements are carried out to evaluate the performance of the approach. Conclusions are given in Section V.

II. State of Art

A. Cooperative Intelligent Transport System (C-ITS)

In Europe, the 5GHz frequency band is allocated for V2X communications to enable short-range and low-latency C-ITS communications. The ITS-G5 technology is based on IEEE 802.11p [2]. The table below details the frequency allocated for C-ITS in Europe.

TABLE I
Frequency allocation in the European Union [2]

	Frequency Width [MHz]	Usage
ITS-G5D	5905 - 5925	Future ITS applications
ITS-G5A	5875 - 5905	ITS road safety related applications
ITS-G5B	5855 - 5875	ITS non-safety applications
ITS-G5C	5470 - 5725	RLAN (BRAN, WLAN)

The ITS road safety applications use the frequency band defined by ITS-G5A. The exchange of the traffic messages (CAM: Cooperative Awareness Messages), the event messages (DENM: Decentralized Environmental Notification Messages), the requests to get the certificates to the PKI (Public Key Infrastructure) and further the transaction in the air occur in this band.

B. Electronic Toll Collection System (ETC system)

Electronic toll collection first appeared in the early eighties, in the United States (Texas) and in Europe (France in 1985, Norway in 1986, etc.) [1].

Today in France, we can distinguish the ETC system with stop-and-go scenario for the majority of tolls, and the free-flow scenario. For the stop-and-go situation, when the driver crosses the tollgates, different means of payment are provided by the motorway operator to collect toll fees: by cash, by electronic payment card, by NFC, by Dedicated Short Range Communication (DSRC)[1] equipment. For all these means, the suitable system of detection of the vehicle and the validation of the ETC transaction has to be deployed in every lane. For example, for the DSRC system, in each lane, there is a RoadSide Unit (RSU) that can detect with accuracy the vehicle in front of the tollgate with the On-Board Unit (OBU) which is placed on top of the windshield, and then perform the transaction.

Other systems use the ANPR[2] technology to perform the tolling transactions [3]. But in this situation, the number of deployed and operational cameras must be at least the number of lanes. It means that the cost of installation and maintenance of those equipment will be more considerable.

[1]DSRC in Europe has a different meaning than in the US
[2]Automatic Number-Plate Recognition

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With the deployment of C-ITS in cars and on European roads in the coming years, million of vehicles will include a powerful communication system that will provide them with new safety and mobility services. By this way, the same device permits both to communicate to other vehicles or the infrastructure and to pay the toll fees in highway. And the real challenge is to use just one RSU to interoperate with all the connected vehicles in the toll area from all directions. The RSU has to ensure both a reliable vehicle location to validate the transaction in the right lane, and a secure communication during the transactions. These are the requirements to perform this service.

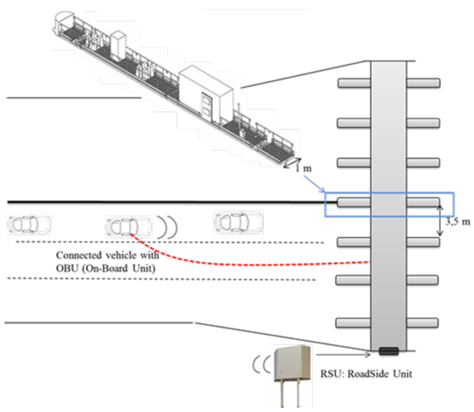

Fig. 1. ETC system with C-ITS (stop-and-go scenario)

The figure 1 illustrates the importance of the high precision of the vehicle location. For the stop-and-go situation, in each lane there is a gate that will just open when the ETC transaction is well performed (detection of the vehicle + ETC identification information)

III. Approach to Perform the ETC Transaction with C-ITS

A. General description of the method

In this context of new ETC system with C-ITS, our approach is to use just one RSU to detect all the connected vehicles crossing the tollgates. To do so, the idea is to take advantage of the communications data: CAM messages exchanged between vehicles and infrastructure.

The CAM messages contain the measurements from the sensors of the vehicle. The figure below presents the CAM structure:

ITS PDU header	Basic Container	HF Container	LF Container (Conditional)	Special vehicle Container (conditional)
		Vehicle HF Container	Vehicle LF Container	Public Transport Container
		Other containers	Other containers (not yet defined)	Special Transport Container
				...

Fig. 2. CAM structure [4]

Where the containers are described as follow:

TABLE II
CAM Definition [4]

Container	**Data elements**
ITS PDU header	Protocol version
	Message ID
	Station ID
	Generation delta time
Basic Container	Station Type
	Reference Position
High Frequency Container	Heading
	Speed
	Drive Direction
	Vehicle Length
	Vehicle Width
	Longitudinal Acceleration
	Curvature
	Curvature Calculation Mode
	Yawrate
	Steering wheel angle
	Lateral acceleration
	Vertical acceleration
Low Frequency Container	Vehicle Role
	Exterior Lights
	Path history

These messages are handled in real time (about 10 Hz) by the RSU and contain vehicle states such as GPS coordinates, speed, and other interesting information that will help us to better estimate its location. So, by means of these measurements, the RSU will evaluate the car position until it comes in front of the toll gate.

The figure below sums up the process as long as the RSU receives CAM from the vehicles allowed to use the application.

Get CAM from each vehicle
↓
Extract position, speed, acceleration, heading, steering wheel angle, yawrate
↓
Add the information about itself (delta position of the RSU)
↓
Apply suitable filter according to the motion model of the vehicle (Kalman filter, extended Kalman Filter
↓
Get the reliable position

Fig. 3. Loop process as long as the RSU gets CAM from each vehicle

B. Background on tracking

The estimation of vehicle location is one of the most important data fusion tasks for intelligent traffic applications. Nowadays, many cars are delivered from the factory with a GPS-based in-car navigation system. It is a real challenge to use this low-cost sensor technology to have high-performance navigation system [5]. The field of aviation, agriculture, traffic systems, emergency systems, surveying and many others successfully employ GPS [6], [7], [8], and [9].

To achieve our goal, we remind the fact that a tracking is necessary to predict the lane where will be the vehicle when crossing the tollgate. For the infrastructure, knowing the lane where is the vehicle permits to trigger command (OPEN) to the gate in the concerned lane.

1) Delta position: In our approach, we calculate the differential of the position of the vehicle by means of the differential computed on the RSU. In fact, the RSU has a static real position and a GPS measurement. So, it is the gap between these 2 values that we apply for the position of the vehicle. Obviously, we have supposed that for C-ITS in closed position, the error of the GPS measurement is the same (inspired by the principle of Differential-GPS where the RSU is like the fixed station).

2) Suitable filter for a suitable system model: After adding the delta position to the GPS received from the OBU, we improve accuracy of the vehicle's trajectory by applying a suitable filter that takes into consideration the available measurements.

For the prediction of the vehicle trajectory, many models are proposed in the literature to solve this issue according to the applications [10], [11], [12], and [13]. For our application, we try different models by using the interesting information available in the CAM messages: GPS coordinates, speed, acceleration, yaw rate, steering wheel angle. These latter will help to define the behaviors of interest of the vehicle including turning, accelerating and braking. According to the value of each parameter, we can set the vehicle into four states, that will be illustrates in the figure below:

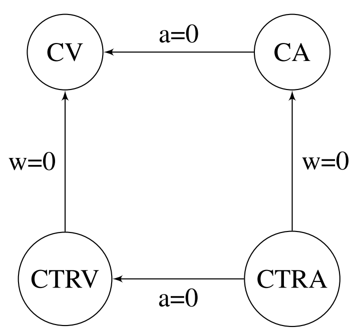

Fig. 4. State of vehicle motion changes by setting one variable to zero

Where CV, CA mean constant velocity v, acceleration motion a in straight-line travel; CTRV means constant turning w and constant velocity motion and CTRA constant turning and constant acceleration travel.

CV: is a linear motion model ($\widehat{X}_k^- = F_k.\widehat{X}_{k-1}^+$), with the state vector $X_k = (x_k, y_k, v_{x_k}, v_{y_k})$ and the transition matrix:

$$F_k = \begin{pmatrix} 1 & 0 & dt_k & 0 \\ 0 & 1 & 0 & dt_k \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{1}$$

CA: is a linear motion model ($\widehat{X}_k^- = F_k.\widehat{X}_{k-1}^+$), with the state vector $X_k = (x_k, y_k, v_{x_k}, v_{y_k}, a_{x_k}, a_{y_k})$ and the transition matrix:

$$F_k = \begin{pmatrix} 1 & 0 & dt_k & 0 & \frac{1}{2}dt_k^2 & 0 \\ 0 & 1 & 0 & dt_k & 0 & \frac{1}{2}dt_k^2 \\ 0 & 0 & 1 & 0 & dt_k & 0 \\ 0 & 0 & 0 & 1 & 0 & dt_k \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \tag{2}$$

CTRV is a non-linear motion model with the state vector $X_k = (x_k, y_k, \theta_k, v_k, w_k)$ and the transition equation:

$$\widehat{X}_k^- = \widehat{X}_{k-1}^+ + \begin{pmatrix} \frac{v}{w}\sin(wdt_k + \theta(t)) - \frac{v}{w}\sin(\theta(t)) \\ \frac{v}{w}\cos(wdt_k + \theta(t)) - \frac{v}{w}\sin(\theta(t)) \\ wdt_k \\ 0 \\ 0 \end{pmatrix} \tag{3}$$

Where θ is the direction of the vehicle.

Also, CTRA is a non-linear motion model that takes into a consideration all the parameters as long as they are different from zero. The state vector is $X_k = (x_k, y_k, \theta_k, v_k, a_k, w_k)$.

$$\widehat{X}_k^- = \widehat{X}_{k-1}^+ + \begin{pmatrix} \Delta x \\ \Delta y \\ wdt_k \\ adt_k \\ 0 \\ 0 \end{pmatrix} \tag{4}$$

Where:

$$\Delta x = \frac{1}{w^2}((v(t)w + awdt_k)\sin(wdt_k + \theta(t)) + \\ a\cos(wdt_k + \theta(t)) - v(t)w\sin(\theta(t) - a\cos(\theta(t)))$$

$$\Delta y = \frac{1}{w^2}((-v(t)w + awdt_k)\cos(wdt_k + \theta(t)) + \\ a\sin(wdt_k + \theta(t)) + v(t)w\cos(\theta(t) - a\sin(\theta(t)))$$

For the equations (1) and (2), we apply Kalman filtering to the system, and for the equations (3) and (4), we use the extended Kalman filtering. In fact, the linear models are implemented in the standard form of Kalman filtering, and the nonlinear models in the extended Kalman filtering [13]. The transition equations (3) and respectively (4) are obtained mathematically (differential system) from the hypothesis constant speed and turning, respectively constant acceleration and turning. We remind in the figure 5 the vehicle schematic.

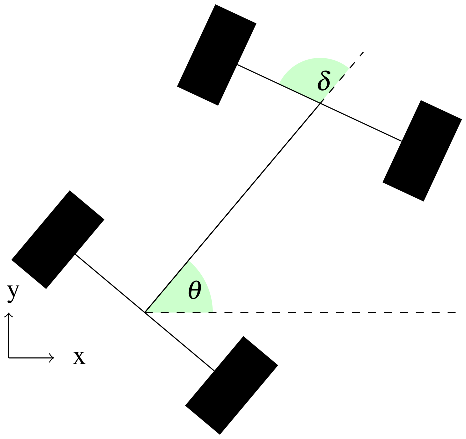

Fig. 5. Vehicle schematic

Where x, y are the Mercator projections of the latitude and the longitude. θ is the direction of the vehicle, and δ is the steering wheel angle.

C. Filter Algorithm

The Kalman filtering (KF) is named after Rudolf E. Kalman, who published his famous paper describing a recursive solution to the discrete-data linear filtering problem in [15]. In a discrete context, the KF is a recursive estimator. It permits to estimate the current state with only the estimation of the previous state and the current measurements. The history of observations and estimations is not required. However, for non-linear problem, using the KF is not suitable. For non-linear systems, the extended Kalman filtering (EKF) can be applied. The system model has just to be differentiable. As a reminder, let's formulate the process of the EKF. Considering the state transition and observation models:

$\widehat{X}_k^- = f(\widehat{X}_{k-1}^+, u_k) + w_k$; $z_k = h(\widehat{X}_k^-) + v_k$

Where u_k is the control vector, w_k and v_k are the process and observation noises with the covariance matrix Q_k and R_k respectively. Because we just evaluate or track the real position of the vehicle; there is no u_k term since we have no known control inputs. Similarly to the KF, the EKF [16] is also composed by two stages:

Prediction stage:

- $\widehat{X}_k^- = f(\widehat{X}_{k-1}^+) + w_k$, is the predicted state
- $P_k^- = F_k P_{k-1}^+ F_k^T + Q_k$, is the predicted covariance matrix

Update stage:

- $K_k^- = P_k^- H_k^T (H_k P_k^- H_k^T + R_k)$, is the Kalman gain optimal
- $\widehat{X}_k^+ = \widehat{X}_k^- + K_k(z_k - H_k \widehat{X}_k^-)$, is the updated state
- $P_k^+ = (I - K_k H_k) P_k^-$, is the updated covariance estimation matrix

Where

$$F_k = \left.\frac{\partial f}{\partial X}\right|_{\widehat{X}_{k-1}^+},$$

and

$$H_k = \left.\frac{\partial h}{\partial X}\right|_{\widehat{X}_{k1}^-}$$

the Jacobians of the state transition and observation models.

IV. Simulation and Results

First, we remind that here we do not yet use the delta position, we are just evaluating the performance given by the filters according to the models in our configuration. For the ETC transaction, we are most of the time in highways, with high speed and generally on straight-line travel. To test the performance of all the models, we target the vehicle from a point A to point B as we can see in the figure below.

Fig. 6. Trajectory of the test travel

The evolution of the speed during this test is given by the figure below:

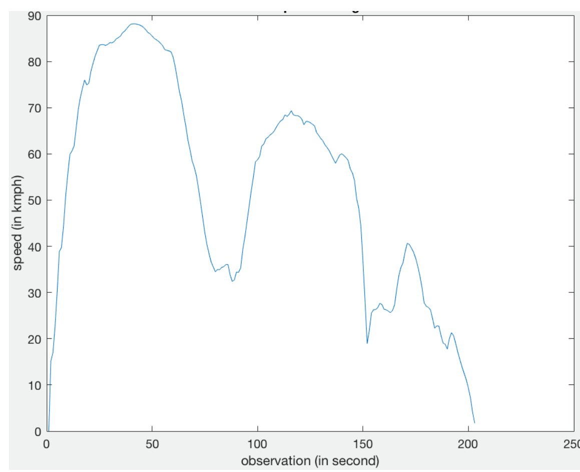

Fig. 7. The evolution of the speed from A to B

During this travel, we save the measurements in the CAM message.

After, as a post-processing operation, we apply each model to our measurements. And we compare the result to the reference trajectory.

As results of the simulation, we can establish the comparison below:

According to the TABLE III, we observe that the EKF applied to the system that takes into a consideration all the measurements are more reliable (acceleration, turning rate). With the condition of our travel (starting, round about, stopping), the system model CTRA evaluates better the

TABLE III

COMPARISON BETWEEN THE GPS ERROR, THE ESTIMATED POSITION OBTAINED BY THE KALMAN FILTERING WITH CONSTANT SPEED AND CONSTANT ACCELERATION, AND OBTAINED BY THE EXTENDED KALMAN FILTERING WITH CONSTANT TURNING RATE, CONSTANT SPEED AND CONSTANT ACCELERATION

Method	Sum of mean square error during the travel (m)
measurements	37.76
KF applied to CV	36,18
KF applied to CA	37,74
EKF applied to CTRV	37.76
EKF applied to CTRA	35.40

vehicle location. We can observe in the figure below the difference between the measurement, the reference and the estimated trajectory by the EKF with CTRA model especially on the roundabout:

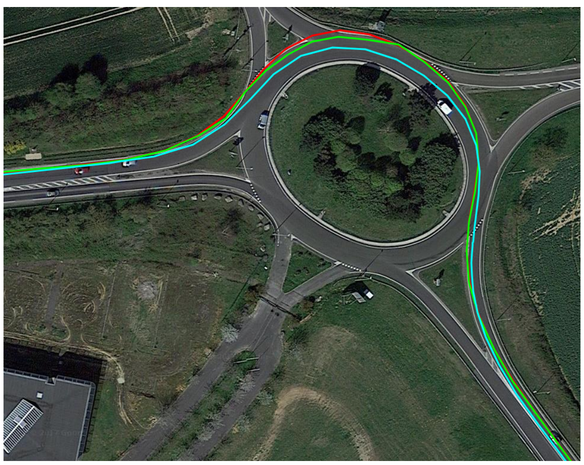

Fig. 8. Evolution of the vehicle location on the roundabout portion of the path

The path in blue color represents the real trajectory, the path in red color represents the measurement and the estimated trajectory is in green color. The estimated trajectory seems to be nearer the real trajectory than the measurement. Indeed, this curve configuration is present in some cases before arriving at the toll station. Also, we treat this situation to evaluate the performance for each model.

But, we have also to remind that for our application “ETC transaction generally in highways”, the speed is almost constant and the roundabout is not present in highways. For that the system model with constant velocity has to be considered. And that is the reason why also in the result TABLE III, the KF with constant velocity appears efficient after the system model CTRA. In the paper [17], we already demonstrated the efficiency of applying KF with constant velocity and where the acceleration is considered as a noise of the model. During the straight-line trajectory, this latter is more efficient. Indeed, for our goal, interacting the two models is the most reliable, because it takes into a consideration all the behaviors of the vehicle and all the possible configurations of the roads.

V. CONCLUSIONS

The Cooperative Intelligent Transportation Systems offer new opportunities and new services for both the drivers and the road operators. In this context, we offer an innovative toll collection service. And in this paper, we proposed a solution for the requirement of a reliable vehicle location for the ETC transactions service.

To do so, we just use one RSU to perform the tracking of the vehicle during ETC transaction. The method takes advantages from the exchanged messages CAM between vehicles and infrastructure. Then the process of filtering is applied to the measurements retrieved from the communication (GPS coordinates, speed, acceleration, yaw rate, steering wheel angle).

For the tracking, the definition of the suitable system model is a big challenge. We demonstrate in this paper that taking into a consideration all the measurements by choosing the system model CTRA (Constant acceleration with constant turning rate) is more reliable than other models to be adaptable in different situations, especially in case of critical manoeuver from the driver. But in highways, considering the amount of straight-line road, interacting the two models CV and CTRA are more efficient. In fact, applying Kalman filtering for CV requires a time of computation lower than applying Extended Kalman filtering for the CTRA model.

It is necessary to perform the ETC service with the ITS-G5 technology. Now, this method is under test and validation process. Adding to this work, we are investigating on the security of the ETC transaction for C-ITS.

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