Influence of Vehicle Characteristics on an Inductive Sensor Model for Traffic Applications

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Abstract — In this work we model an inductive loop detector with the purpose of studying the influence of significant vehicle characteristics on the obtained inductive signatures. Since this model will allow us to obtain the vehicle inductive signatures by means of a simulator without making use of expensive, not only in time but also in resources, tests in real scenarios, we will have a powerful tool to test some features of our inductive sensor prototype in advance. As shown with the results obtained using both the prototype and the inductive sensor simulator, the vehicle signatures exhibit similar characteristics in time and frequency domains, which validates the model used in this work. Moreover, several simulation results will show the impact of some physical parameters, such as the distance between the vehicle undercarriage and the loop under the road pavement, vehicle length or width, and its speed or acceleration, on their corresponding inductive signatures in both time and frequency domains. Additionally, a spectral feature extracted from the signatures in the frequency domain is studied using our software, giving us as a result that such an indicator suffers negligible variations with all the tested vehicle characteristics except for length, which is directly related to the type of vehicle. This remarkable dependence can be exploited for vehicle classification tasks.

Keywords - circuits and devices; inductive sensors; intelligent transportation systems; sensor modelling; signal processing; simulator; spectral analysis

I. INTRODUCTION

Inductive Loop Detectors (ILDs) are sensors widely used in traffic management systems [1], [2], [3], [4]. There exist different implementations of ILDs for this purpose. In the US4680717A patent [5], a multiplex system for vehicular traffic detection with a single oscillator is presented. Recently, a detector of multiple vehicles requiring multichannel acquisition of analog signals has been developed [6], but it is overly complex and, due to the function not being fully multiplexed and to the use of the same frequencies in near loops, it presents significant interferences between channels. In [7], we proposed a multiplex system for a Simple Detector of Inductive Vehicle Signatures (SiDIVS). Our proposal implies a fully multiplexed system that avoids the interference between loops thanks to a very simple and almost fully automatic digital measurement process. Therefore, it does not require neither the use of complex and expensive analog processing circuits nor of analog signal acquisition methods.

Most traffic classification systems need accurate and reliable speed estimation with the shortest possible time delay to determine control strategies. Traffic speed estimation using dual loop detectors can be accurate for most cases [8] but it requires an appropriate maintenance of the two loops. Moreover, most loop stations in traffic operation are still single-loop. Although several algorithms have been developed for single-loop speed estimation, how to obtain an enough accuracy is still an open question [9], [10]. Therefore, the design of a strategy for vehicle classification to be robust against speed variations using only one loop has been a strong motivation for the authors work. Thus, we have proposed in [11] a method based on analysing the inductive signatures in the frequency-domain instead of working in the time-domain, which provided greater accuracy than other threshold-based methods using standard criteria, such as the vehicle length estimation. Also in that work, this spectral method has been tested using inductive signatures captured with our prototype (SiDIVS) at two difference places in Galician, the AC-523 road (Ledoño Meirama, Spain), and the AC-415 road (Pastoriza-Arteixo, Spain), for vehicle classification purposes.

However, the high cost associated with testing every new development in real environments leads to the need of an appropriate model of the inductive sensor so that a simulator can be employed to assess their performance without wasting time and resources. With that purpose, in this paper we study a model of the proposed inductive loop sensor that will be employed to study the influence of parameters such as vehicle speed, acceleration, height, width and length in vehicle classification strategies.

This paper is organized as follows. Section II briefly describes the time and frequency analysis of real vehicle inductive signatures whose behaviour will be replicated with the proposed model. Section III details the model for the inductive sensor that will be employed by the simulator. Section IV presents two experimental results obtained with
our proposed simulator of vehicle inductive signatures, that we name SimSiDIVS (Simulator for SiDIVS). Finally, Section V is devoted to conclusions and final remarks.

II. TIME AND FREQUENCY ANALYSIS FROM REAL INDUCTIVE SIGNATURES

This section will briefly summarize the time and spectral features extracted from real vehicle inductive signatures, which will be modelled in the following section. Those real inductive signatures have been obtained with our hardware prototype SiDIVS [7].

Fig. 1 shows two real signatures captured with SiDIVS: one corresponding to a car and another one to a van. For each example, the upper part corresponds to the desired time feature i.e., the acquired signature in the time domain, which has been normalized with respect to its maximum value. The bottom part is the signature in the frequency domain, obtained by means of the Fast Fourier Transform (FFT) algorithm, with a sampling frequency of 100 Hz and normalized with respect to the coefficient at the frequency bin \( f = 0 \). The maximum frequency bin after \( f = 0 \) is marked with a dark line in the corresponding figures. Note also that, as it can be concluded after observing the Fourier Transform (FT) of the example of the van, the first peak is higher compared to that obtained for the car example. According to that, the proposed spectral feature, denoted as \( \hat{c} \), can be calculated as

\[
\hat{c} = \frac{\max(|H(f) > 0|)}{|H(f = 0)|}.
\]

where \( H(f) \) represents the Fourier coefficient at the frequency bin \( f \). This spectral feature directly extracted from the FT has been used in [11] by the authors to classify the vehicles passing on the roads under test, and it has also been shown in that work how the error percentages obtained using the FT-based indicator of (1) are smaller than those achieved with other standard classification strategies studied in related literature.

III. LOOP DETECTOR SIMULATOR

The classical inductive loop is simply a buried wire loop connected to an alternating current source, which also creates an alternating magnetic field. The equivalent model of the set constituted by the inductive loop and the vehicle is shown in Fig. 2.

The assembly formed by the coil and the vehicle undercarriage is modelled by an air core transformer in which the primary coil inductance, denoted by \( L_1 \), is excited by the sinusoidal generator at the oscillation frequency; the secondary, which represents the vehicle undercarriage, is modelled by a turn in short circuit with an inductance denoted by \( L_2(k) \), whose value changes with the vehicle position on the coil located under the road pavement and therefore depends on the time instant \( k \); and finally, the coupling coil-vehicle is modelled by the mutual inductance denoted by \( M(k) \), which also depends of the position of the vehicle on the road coil. This equivalent circuit is shown in Figure 3.

The self-inductance of a loop, in our case the coil placed under the road pavement, and denoted by \( L_1 \), is given by the following expression [12],

\[
L_1 = \frac{\mu_0 N_1^2 A_1 l_1}{I_t},
\]

where \( \mu_0 = 4\pi \times 10^{-7} \) H/m, \( N_1 \) is the number of turns, \( A_1 \) is the cross sectional area of the coil, \( l_1 \) is the axial length of the coil, and \( F_1 \) is a factor used to consider the non-uniform flux in the roadway inductive loop.

As mentioned before, both the vehicle inductance, denoted by \( L_2(k) \), and the mutual inductance, denoted by \( M(k) \), depend on the position of the vehicle over the road loop and therefore, on the time instant \( k \). At that time instant \( k \), the vehicle covers a loop area, \( A_2(k) \), given by

Figure 1. Examples of inductive signatures.

Figure 2. Inductive loop and vehicle model.
where the inductive signature \( \text{is obtained from the air core transformer model of the system} \)

\[
\text{frequency of the circuit is given by}
\]

Finally, the shift in the oscillation period (which gives us the inductive signature) is determined as follows

\[
\Delta T = 2\alpha \left( \sqrt{L_1 C_T} - \sqrt{L_{\text{eq}}(k) C_T} \right),
\]

where

\[
L_{\text{eq}}(k) = \frac{L_1 L_2(k) - M(k)^2}{L_2(k)},
\]

is obtained from the air core transformer model of the system formed by the inductive loop and the vehicle undercarriage.

IV. EXPERIMENTAL RESULTS

In this section we have developed two different experiments to show the performance of our model. In all of them, the inductive signature is obtained with the following procedure. The vehicle profile is placed at the different positions of the vehicle on the road loop, accordingly to the sampling frequency, vehicle and loop lengths, or vehicle speed and acceleration.

Let the origin for the length measurement be that on which the vehicle comes into the loop and \( k = 0 \) the initial time instant corresponding to that event. Thus, we can write that the distance travelled by the vehicle during a total time period \( k \) is given by

\[
x(k) = v_i k + \frac{1}{2} a k^2.
\]

where \( v_i \) is the initial speed at the time instant \( k = 0 \) and \( a \) is the vehicle acceleration, assumed to be constant and straight-line.

From this expression of \( x(k) \), we can directly obtain the vehicle length covering the loop, which is given by \( l_i(k) \). The vehicle inductance \( L_2(k) \) can be easily obtained from (3) and (4). Also from \( l_i(k) \) we can determine the mean distance \( d(k) \) so that the mutual inductance is directly derived using (5).

Taking into account that the loop inductance \( L_1 \) is calculated as given in (2), the equivalent inductance and the shift in the oscillation period \( \Delta T \) can be obtained using (8) and (7), respectively. As said before, \( \Delta T \) gives us the amplitude of the inductive signature for the vehicle passing on the loop under the road pavement, which will be plotted in the figures corresponding to the experiments shown in the next subsections.

In our simulation experiments, we have used the following parameters: \( N_1 = 4, A_1 = 4 \text{ m}^2, l_1 = 7.5 \text{ cm}, l = 600 \text{ cm}, w = 180 \text{ cm}, l_2 = 2.5 \text{ cm}, \) and \( C_T = 50 \text{nF} \).

A. Experiment 1: Time domain analysis

In this experiment we study the behaviour of our model against changes of different vehicle characteristics, such as width, distance between the vehicle undercarriage and the coil under the pavement, length, speed or acceleration. Fig.4 shows the profile of a vehicle of 6 m in length used for those simulations.

1) Influence of the vehicle width: First of all, we want to analyse the influence of the vehicle width on the inductive signatures generated using the procedure explained before. Fig. 5 shows the inductive signatures obtained for a vehicle with the profile of Fig. 4 travelling at a speed of 50 km/h without acceleration. We can see the good linearity of our model against width changes. As shown in the figure, a good proportionality for all the time range of the inductive signature is maintained.

2) Influence of the distance vehicle-loop: Next, we will analyse the influence of the distance between the vehicle undercarriage and the loop under the road pavement for four different profiles: first, for the profile given in Fig. 4, and then for three profiles directly obtained from that after multiplying such a distance by a factor of 2, 3 and 4. For all the cases the vehicle speed is 50 km/h, without acceleration. Again, a good proportionality can be observed, but now with the inverse of the squared distance, since the amplitude of the inductive signature is highly sensitive to distance changes.
3) Influence of the vehicle length: We will study now how the vehicle length influences on the inductive signature. For this purpose, the profile of Fig. 4 is scaled for vehicles of 4, 6, 10 and 16 meters in length without acceleration and travelling at 50 km/h. From Fig. 7, we can conclude that the vehicle length strongly affects the signature for a fixed profile.

4) Influence of the vehicle speed: With the purpose of analysing the effect of the vehicle speed on the inductive signatures, we have obtained the signatures corresponding to the profile of a vehicle of 6 m in length (see Fig. 4) for constant speeds of 50, 100, 150 and 200 km/h with $a = 0$ m/s$^2$. Fig. 8 shows the corresponding scaled replicas in time resulting from those variations in speed.

5) Influence of the vehicle acceleration: Finally, the impact of the vehicle acceleration on the inductive signatures is shown in Fig. 9. We have simulated inductive signatures for the vehicle whose profile is given in Fig. 4 and whose acceleration is 0, 3, 6 or 9 m/s$^2$ with an initial speed of 50 km/h. This effect produces an undesirable distortion in the inductive signature.

B. Experiment 2: Frequency domain analysis

Fig. 10 plots the normalized FT of the inductive signatures for the profile in Fig. 4 scaled to 4, 6, 10 and 16 meters in length. As it can be seen from the figure, an increase in the vehicle length affects the amplitude of the first peak of the FT given by (1), as it occurs with real acquired signatures (see Fig. 1). This effect can be more clearly seen in Table I.

On the other hand, Tables II-V show the spectral feature $\hat{c}$ of (1) as a function of the vehicle width, the distance between the vehicle undercarriage and the loop under the road pavement, the vehicle speed and the vehicle acceleration, respectively. This frequency domain study is similar to the time domain study performed in Subsection IV-A. As can be seen in the tables, although the vehicle length (which is directly related to the type of vehicle) produces significant changes in $\hat{c}$, the other parameters do not have significant influence on this parameter.
TABLE I. Ĉ PARAMETER FOR VEHICLES WITHOUT ACCELERATION AND 50 KM/H OF SPEED AS A FUNCTION OF THE VEHICLE LENGTH (IN M)

<table>
<thead>
<tr>
<th>Length (m)</th>
<th>Parameter Ĉ</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.0190</td>
</tr>
<tr>
<td>6</td>
<td>0.0273</td>
</tr>
<tr>
<td>10</td>
<td>0.0745</td>
</tr>
<tr>
<td>16</td>
<td>0.0946</td>
</tr>
</tbody>
</table>

TABLE II. Ĉ PARAMETER AS A FUNCTION OF THE VEHICLE WIDTH (IN CM)

<table>
<thead>
<tr>
<th>Width (cm)</th>
<th>Parameter Ĉ</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.0305</td>
</tr>
<tr>
<td>100</td>
<td>0.0287</td>
</tr>
<tr>
<td>150</td>
<td>0.0278</td>
</tr>
<tr>
<td>180</td>
<td>0.0273</td>
</tr>
<tr>
<td>200</td>
<td>0.0271</td>
</tr>
</tbody>
</table>

TABLE III. Ĉ PARAMETER AS A FUNCTION OF THE DISTANCE BETWEEN VEHICLE AND LOOP (GIVEN BY THE PROFILE IN FIGURE 4)

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Parameter Ĉ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>0.0273</td>
</tr>
<tr>
<td>X2</td>
<td>0.0277</td>
</tr>
<tr>
<td>X3</td>
<td>0.0278</td>
</tr>
<tr>
<td>X4</td>
<td>0.0278</td>
</tr>
</tbody>
</table>

TABLE IV. Ĉ PARAMETER AS A FUNCTION OF THE VEHICLE SPEED (IN KM/H)

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Parameter Ĉ</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.0273</td>
</tr>
<tr>
<td>100</td>
<td>0.0280</td>
</tr>
<tr>
<td>150</td>
<td>0.0263</td>
</tr>
<tr>
<td>200</td>
<td>0.0273</td>
</tr>
</tbody>
</table>

TABLE V. Ĉ PARAMETER AS A FUNCTION OF THE VEHICLE ACCELERATION (IN M/S²)

<table>
<thead>
<tr>
<th>Acceleration</th>
<th>Parameter Ĉ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0273</td>
</tr>
<tr>
<td>3</td>
<td>0.0292</td>
</tr>
<tr>
<td>6</td>
<td>0.0304</td>
</tr>
<tr>
<td>9</td>
<td>0.0313</td>
</tr>
</tbody>
</table>

V. CONCLUSION

In this paper we have presented an appropriate model of an inductive loop detector. As it can be seen from the results, the vehicle inductive signatures obtained with the simulator SimSiDIVS that we have developed employing this model are similar to those directly obtained from the real scenario with our hardware prototype.

Thanks to this simulator, we have demonstrated that the FT parameter described in the paper exhibits robustness against variations in most vehicle physical characteristics such as speed, acceleration, vehicle-road loop distance or width. However, this parameter is very sensitive to changes in vehicle length, which can be easily exploited in vehicle classification strategies. These prior studies reduce costs by avoiding tests in real scenarios and also allow us to develop new vehicle classification techniques.

We are working on the development of a sensor model that is more sophisticated than the one presented in this paper and that better fits the real sensor behaviour under all the possible scenarios. This model will consider not only the penetration depth of the Foucault currents induced in the road coil but also both the influence of the coil pieces of the vehicle undercarriage that are not directly over the road coil and the influence of the neighbouring coils.

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REFERENCES


