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Estimating vehicle speed with embedded inertial sensors

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A R T I C L E I N F O

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Pavements were instrumented with inertial sensors, and the possibility of estimating the speed of a passing vehicle was investigated numerically and experimentally from the measurements of two embedded accelerometers. The sensors were spaced apart in the travel direction, and subsequently the speed was directly related to the time delay between the received signals. No assumption was made regarding the vehicle and pavement properties. Model accelerations were presented, studied, and contrasted against field measurements; the latter were shown to be dominated by random vibration sources. Two calculation techniques were offered and applied to handle the noisy data. The first was based on time-centroids, and the second was based on cross-correlation with kernel presmoothing. The overall concept is deemed promising not only for inferring speeds but also for extracting additional traffic characteristics such as axle spacing and relative axle load distributions.

1. Introduction

Inertial sensors (accelerometers) monitor velocity rates in one, two, or three perpendicular directions. Due to increased commercial demand, accelerometer technology has greatly improved in recent years in terms of sensitivity, frequency response, physical size, and power consumption (Wilson, 2005; Fraden, 2010). For these reasons accelerometers are deemed ideal candidates to serve as pavement sensors for wide-area instrumentation. A pavement containing implanted accelerometers can offer ‘internal’ data about the displacement field generated by passing vehicles. In principle, this data can be acquired at any point in time during the life of the system and without interrupting traffic flow.

The incentive for embedding acceleration sensors in pavements is twofold. First, it can assist in monitoring the mechanical properties of the different pavement layers. Such information is important to pavement managers dealing with health monitoring and scheduling of maintenance activities. Second, the sensors can potentially detect traffic characteristics such as vehicle speed, axle spacing, axle weight distribution, and wander position. This information is of interest to transportation managers dealing with traffic flow rates, lane capacities, and vehicle type classification. It is important to note that both applications are effectively intertwined because the inference of mechanical properties from embedded sensors employs an inverse analysis scheme which requires traffic characteristics to be a priori specified (Arraigada et al., 2009; Levenberg, 2012, 2013). Despite the abovementioned possible applications, this field of study is still in its embryonic stage, with very few applications reported in the literature.

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This study sets out to explore the ability of estimating a vehicle speed from the joint measurements of two inertial sensors embedded in the pavement. Unlike traditional non-intrusive speed detection technologies such as cameras, radar systems, light barriers, or pneumatic tubes, accelerometers reside in the pavement and therefore are relatively well protected from weather disruptions and vandalism. Also, since the measuring device is concealed, driving speed and driver behavior are not affected. Additionally, compared with other intrusive technologies such as induction loop detectors or pressure sensors, the low pricing and low installation costs of accelerometers (especially if wireless) make their possible usage extremely appealing. At this time, the testing and analysis will only focus on single-axis accelerations measured in the vertical direction (more precisely, normal to the pavement surface).

In terms of setup and installation, the most closely related works to the current effort deal with using road surface vibration measurements to perform traffic counts (Hostettler et al., 2009; Hostettler, 2009). In these studies an accelerometer was fixed inside an asphalt road near the surface, measuring vertical in-pavement response of passing vehicles. The data was then used for detecting and counting the passage of nearby vehicles. An attempt to deduce travel speeds from frequency shifting (i.e., Doppler effect) was reportedly unsuccessful; short time Fourier analysis was performed but no systematic shift was detected in the transform spectrograms. Another closely related effort to the current is by a group from Berkley (Haoui et al., 2008; Bajwa et al., 2011; Ma et al., 2014). The developments of this group aim at managing traffic and hence focus on detecting (counting) vehicles, estimating speeds, and classifying types. This information is sought by means of wireless sensor nodes implanted close to the surface. In general, each node consists of a magnetometer for detecting vehicles and measuring speeds; every node is also equipped with a single axis accelerometer for estimating axle spacing (allowing subsequent type classification). Herein the speed estimation is based exclusively on accelerometer readings, allowing the sensors to be deepened significantly. So doing permits (also) reliable inference of mechanical pavement properties which is the ultimate intention of this project (not the objective here though); another advantage is escaping the need to replace units due to routine resurfacing.

In terms of interpretation approach, the most closely related works to the current effort deal with estimating vehicle speed from a two-microphone array (Pérez-González et al., 2002; López-Valcarce et al., 2004; Duffner et al., 2005). In these papers algorithms were proposed and explored for estimating the speed of passing cars from the readings of a pair of omnidirectional microphones located on the roadside. The microphones are spaced apart parallel to the travel direction by a known and predetermined distance. The speed estimation did not make any assumption on the acoustic signal emitted by the passing vehicles; the only assumption made was that the sound recorded by the microphones, while interlaced with some random noise, was essentially similar. Subsequently, the delay between the signals was sought as means of inferring the speed. Promising results were reported by the researchers along with the identification of several open questions, e.g., how to deal with the presence of multiple vehicles in the observation window, assessment of the methodology robustness, and selection of optimal sampling frequency. Herein, similarly, the speed estimation will also assume none or negligible a priori knowledge regarding the source signal. The potential of acoustic methods to detect traffic characteristics remains an ongoing research topic (Marmaroli et al., 2011; Barbagli et al., 2012).

2. In-pavement accelerations

To provide some insight into the governing elements of the vertical in-pavement acceleration response, a simple model is interrogated. The model consists of a single wheel traveling over a half-space that is linear elastic, homogenous, isotropic, and weightless. The tire-pavement contact is represented by a vertically (and uniformly) loaded circle that moves across the top boundary along a perfectly smooth straight line. Fig. 1 shows a plan view of this model; a Cartesian coordinate system is positioned such that the x and y axes coincide with the surface and the z-axis (not shown) is directed into the medium. The loaded circular area moves parallel to the x-axis with a constant speed V along the $y = y_0$ line.

The passing load event deforms the entire medium, and the resulting displacement field is computed without considering inertia. So doing is permissible because the travel speed is much slower compared with the velocities of all stress-wave types in the medium. For a virtual accelerometer embedded under $x = y = 0$ and at a depth z_0 from the surface, the quasi-static vertical deflection at the point of embedment is (Van Cauwelaert, 2004):

$$u_z(t) = \frac{qa(1+\nu)}{E}\int_{m=0}^{\infty}\frac{J_0(mr)J_1(ma)}{m}(2-2\nu+mz_0)e^{-mz_0}dm \qquad (1)$$

where $u_z(t)$ is the z-axis displacement at time t, q is the stress intensity, a is the radius of the circular contact, E and ν are the elastic constants of the half-space, m is an integration parameter with units reciprocal to stress, and $J_n(\cdot)$ denotes a Bessel

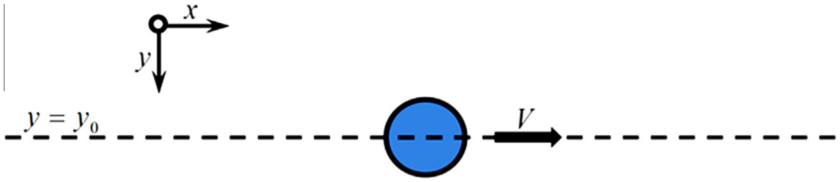

Fig. 1. Plan view of a traveling single wheel model.