Smart Structures and Systems, *Vol. 19, No. 2 (2017) 151-161*
DOI: https://doi.org/10.12989/sss.2017.19.2.151

IRI estimation using analysis of dynamic tire pressure and axle acceleration

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(Received April 12, 2016, Revised August 24, 2016, Accepted August 26, 2016)

Abstract. A new method is developed to estimate road profile in order to estimate IRI based on the ASTM standard. This method utilizes an accelerometer and a Dynamic Tire Pressure Sensor (DTPS) to estimate road roughness. The accelerometer measures the vertical axle acceleration. The DTPS, which is mounted on the tire's valve stem, measures dynamic pressure inside the tire while driving. Calibrated transfer functions are used to estimate road profile using the signals from the two sensors. A field test was conducted on roads with different quality conditions in the city of Brockton, MA. The IRI values estimated with this new method match the actual road conditions measured with Pavement Condition Index (PCI) based on the ASTM standard, images taken from an onboard camera and passengers' perceptions. IRI has negative correlation with PCI in general since they have overlapping features. Compared to the current method of IRI measurement, the advantage of this method is that a) the cost is reduced; b) more space is saved; c) more time is saved; and d) mounting the two sensors are universally compatible to most cars and vans. Therefore, this method has the potential to provide continuous and global monitoring the health of roadways.

Keywords: road roughness detection; International Roughness Index (IRI); dynamic tire pressure; mobile sensing; road health monitoring; Pavement Condition Index (PCI)

1. Introduction

The United States is currently in the midst of an aging civil infrastructure crisis. According to the 2013 infrastructure report card from the American Society of Civil Engineers (ASCE), a ranking of D+ was given for the entire infrastructure system and a ranking of D was given for the roads (ASCE, 2013). This grade increased from a ranking of D and D- for the entire infrastructure system and roads, respectively, in 2009 (ASCE, 2009). Approximately $101 billion was wasted on time and fuel annually due to congested roads (ASCE, 2013). About four million miles of roads in the US requires a broad range of maintenance activities (FHWA, 2008). Around $91 billion was invested annually on roads, but that amount is still insufficient (ASCE, 2013). According to estimates from the Federal Highway Administration (FHWA), approximately $170 billion is needed annually to significantly improve road conditions and performance (ASCE, 2013). Repairing all deteriorated sites is a difficult task because officials in charge of road maintenance have limited resources to allocate. In order to best prioritize road maintenance, the level of deterioration must be known for all roads in a city's network.

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Road inspection data can aid officials in prioritizing road maintenance decisions, which allows them to be more efficient with their resources. Road inspection data can be comprised of results from trained inspection teams, rapid mobile inspection technologies, and even pedestrian reports obtained via social media. Data may be stored in a database or analyzed in real time. The results of damaged sites can be prioritized and used for both short and long term health monitoring of road ways. The present work provides one means for collecting large amounts of data on road health to aid in the planning or road maintenance.

1.1 International Roughness Index (IRI)

The International Roughness Index (IRI) is an important index to assess overall condition and health of roadways and is widely used in the United States. It was established in 1986 by the World Bank and has been widely used since then. IRI measures both the road roughness and drivers' comfort level. IRI carries the unit of slope in m/km or inch/mile. This means IRI indicates the vertical displacement in meters (inches) after travelling one kilometer (mile). A low IRI value indicates smooth road while a high value indicates a rough, deteriorated road that is uncomfortable and dangerous to drive on. The full IRI definition is defined by its creator as the following (Sayers, 1995),

"1) IRI is computed from a single longitudinal profile. The sample interval should be no larger than 300 mm for accurate calculations. The required resolution depends on the roughness level, with finer resolution being needed for smooth roads. A resolution of 0.5 mm is suitable for all

 ISSN: 1738-1584 (Print), 1738-1991 (Online)

conditions.

2) The profile is assumed to have a constant slope between sampled elevation points.

3) The profile is smoothed with a moving average whose base length is 250 mm.

4) The smoothed profile is filtered using a quarter-car simulation, with specific parameter values (Golden Car), at a simulated speed of 80 km/h (49.7 mph).

5) The simulated suspension motion is linearly accumulated and divided by the length of the profile to yield IRI. Thus, IRI has units of slope, such as inches per mile or meters per kilometer."

The meaning of IRI is shown in Fig. 1. At a speed of 80 km/h for vehicles driving on the road, profile information between 1.3 m - 30 m contributes to the IRI calculation. Wavelengths outside this band such as hills and valleys or macrotextures are excluded from the IRI estimation (Sayers *et al*. 1986). Hills and valleys are considered profiles whose wavelengths are larger than 30 m and macrotextures are considered profiles whose wavelengths are smaller than 1.3 m. According to the International Organization of Standardization, the spatial wavelengths of macrotextures are from 0.5 mm to 50 mm (ISO13473-2.2002, 2002).

IRI is commonly calculated using a quarter-car model (also called Golden Car Model) shown in Fig. 2. The variable K_s is the suspension spring rate; C_s is the suspension damping rate; K_t is the tire spring rate; m_s is the sprung mass (portion of vehicle body mass supported by one wheel); m_u is the unsprung mass (mass of wheel, tire, and half of axle/ suspension). The IRI of a road profile is calculated and normalized by the travelling distance L as follows

$$IRI = \frac{1}{L}\int_0^{L/v} |\dot{z}_s - \dot{z}_u| dt \qquad (1)$$

where,
z_s= the height (vertical coordinate) of sprung mass;
z_u= the height (vertical coordinate) of unsprung mass (Sayers, 1995).

$\dot{z_s}$ and $\dot{z_u}$ are temporal derivatives of z_s and z_u respectively representing velocity.

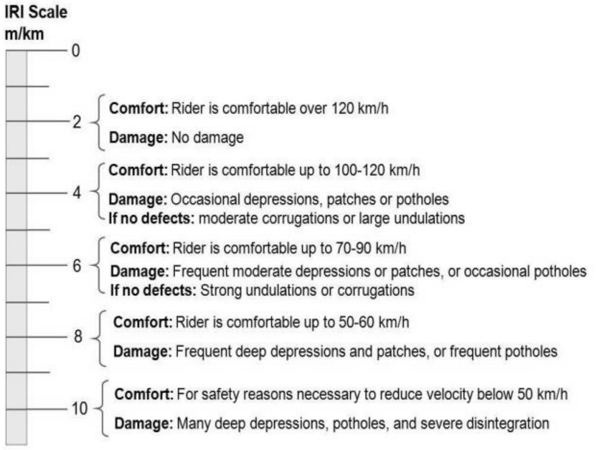


Fig. 1 IRI scale meaning for paved road (E1926-08, 2008)

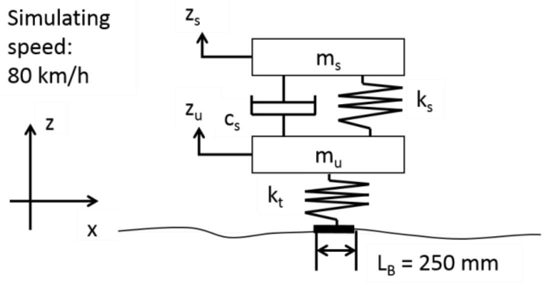


Fig. 2 IRI measurement using Quarter Car model (Sayers1995)

Two major methods are used in the current profile measurement, which are 1) manual profile measurement; and 2) mobile profile measurement. The manual profile measurement requires a person who either pushes a small cart outfitted with profilometers or uses a crutch-shaped profilometer to measure the profile while walking, such as the commercial walking profiler G2 from Arrb Group (arrb 2013) or the Dipstick profiler from FaceCo (Dipstick 2013). One limitation is that these methods can be dangerous for inspectors and drivers on a busy road because they must be done at a walking speed. Depending on how busy the road is, sometimes it needs to be closed, which is inconvenient and expensive for both drivers and contractors. The mobile profile measurement uses a vehicle outfitted with profilometers and accelerometers to measure the profile at a driving speed. One of the best known and earliest non-contact profilers was developed by the South Dakota DOT and is still referred to as the South Dakota Profiler (TRB, 2004). Ultrasonic sensors were used as profilometers that measure the height between the profile and the sensor (Roughness 2012); however, the limitation of ultrasonic height sensors is that they do not operate in winds exceeding 65 km/h (40 mph) (Gillespie 1999). To remedy this, laser profilometers were more frequently used and replaced ultrasonic sensors to measure the height in order to obtain IRI (Texas Department of Transportation, 2012), (Infrastructure Management Services, 2012), (The Swedish National Road and Transport Research Institute, 2012). Wind speed is not an issue for laser profilometers. The road profile is calculated by subtracting double integral of acceleration from displacement from profilometers (Ultra Technoloties 2013), (Viatech 2013), (dynatest, 2013). The cost of laser based sensing equipment and survey is very high. Another method of IRI estimation uses a microphone mounted behind the rear wheel (Zhao 2013). The limitation of this method is that it requires a calibration and complicated signal processing due to the vehicle dynamics and ambient noise.

The new method in this paper overcomes the limitations mentioned above. Additionally, the sensors used are more affordable, more compact, they are compatible with most vehicles (including small cars), and minimal processing power is required to compute results.

In urban roads, many cities use Pavement Condition Index (PCI) to access road conditions. PCI rates from 0 to 100 scale where zero represents "poorest" and one hundred represents "best" surface condition of the pavement. PCI indicates the current condition of the pavement based on the distress observed on the surface of the pavement, the structural integrity and surface operational condition (localized roughness and safety (D6433-11, 2011). However, PCI inspections for cities can be low efficient and objectives due to the measurement. If IRI measurement can indirectly infer PCI values of the road, then the efficiency of the road condition assessment can be increased, therefore, the cost can be saved.

One field test was conducted in New Bedford Airport administered by the Massachusetts Department of Transportation (MassDOT) to test the repeatability. Another field test was conducted in the city of Brockton, MA with the reference of the images taken by a camera along the road track and the feedback from the riders. The estimated IRI values are also compared to the ranking of the Pavement Condition Index (PCI) according to the ASTM standard (D6433-11, 2011) (D5340-11, 2011), (E2840-11, 2011). The results will be discussed in detail in the later sections.

The limitations are that a) this method will not work on hard accelerations or decelerations due to stop signs, traffic lights or hard turns; b) it measures the average road profile over the footprint of the tire/road interaction rather than the point by point road profile measurement from laser profilometers.

1.2 Test equipment

The test vehicle is a 2010 Chevrolet Express cargo van 3500 extended. Multiple sensors are mounted on this van, such as GPS, microphones, MM-wave radar array, laser profilometers, accelerometers, dynamic tire pressure sensor (DTPS), a camera, etc. All the data is collected and stored in multiple single board computers simultaneously inside the van. A continuous network wide health monitoring of road way can be provided from the data fusion from these sensors. The result of road condition assessment and the location data are transmitted back to the main server in real time through a cellular modem. Different sensors are used for different purposes in this research project (Birken 2012), (Birken 2014). In this paper, only the data from the DTPS and the axle accelerometer are discussed in this paper and the camera data and the GPS data are used as a reference.

The dynamic tire pressure sensor is mounted on the valve stem of the left rear wheel and the accelerometer is mounted on the left rear axle shown in Fig. 3. DTPS measures dynamic tire pressure due to the interaction between the road and the tire with a high sensitivity. The axle accelerometer measure vertical accelerations of the rear axle.

The DTPS and the axle accelerometer are installed on the rear driver's side tire and axle because of the following reasons. First, the driver's side tire is far from the engine so less engine noise is introduced to the DTPS. That saves some work on signal processing; second, the tire on driver's side is far from the muffler so less vibration noise from the muffler is introduced. The muffler is on the passenger side; and third, the DTPS data is transmitted through a slip ring assembly while driving. The slip ring has a rod that fixes the data cable connection between the sensor and the data acquisition system inside the van. The rear axle does not yaw independently so the slip ring assembly does not interfere with the body of the van while steering to the right or the left.

A high resolution camera is mounted on the rear of the van through a beam to take surface images of the road every 1.3 m. The width of each image is about 2.1 meters. The images are used as a reference to validate the road condition assessment provided by the DTPS with the axle accelerometer.

2. Theory

This paper focuses on estimating road profile from DTPS with an axle accelerometer measurement. The road profile in this paper is defined as the height of the road relative to a chosen reference height. An assumption is made that the dynamic system comprised of the tire and the suspension of the test vehicle is a linear system. In particular, the dynamic system response to changes in road profile is linear. The response of the dynamic tire pressure and the axle acceleration is the magnitude response to the road profile. Therefore, once the response of the system to one specific height of the road profile is known, the road profiles can be evaluated proportionally to the known profile based on the known response.

The fundamental physics of this method is that the DTPS with an axle accelerometer measures the signals generated from the interaction between the tire and the road due to the road vibration, road profile, and tire wall vibration shown in Fig. 4. The tire wall vibration is not considered in this situation because its frequency range is higher than 500 Hz (Sandberg 2002). The frequency range used in this method is lower than the frequency range of the tire wall vibration (see Section 2.2).

When the vehicle runs on a straight road at a constant speed, the dynamic tire pressure results from the air inside the tire being compressed due to the relative motion between the axle and the road (Pacejka 2005). The tire pressure changes drastically on a rough road, but stays almost constant with minimal change on a smooth road. One advantage of using the tire pressure change is that the tire wall itself also blocks the ambient noise that reduces some work on filtering noise in signal processing. Moreover, due to the location of DTPS, the tire also protects the sensor from humidity.

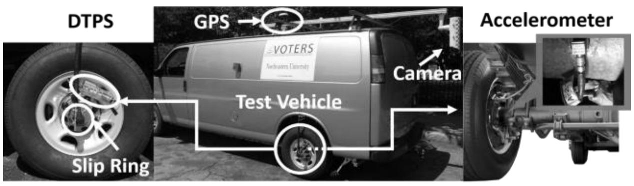


Fig. 3 Sensors mounted on the test van for road profile measurement

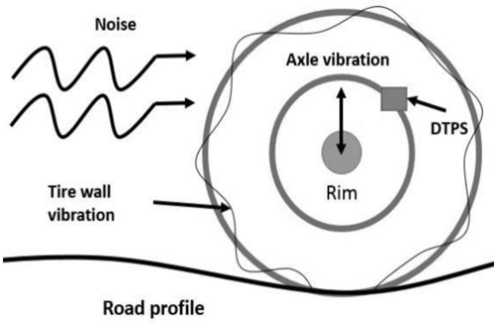


Fig. 4 Physical measurement of road profile using DTPS with an axle accelerometer

The pressure change inside the tire p_{dtps} is recorded with the dynamic tire pressure sensor. This pressure change comprises two parts: a) pressure change due to the road profile denoted as p_{road}, and b) pressure change due to the axle vibrations denoted as p_{axle}.

$$pdtps = proad + paxle \tag{2}$$

The road profile carries the unit of height in cm, and the axle acceleration carries the unit of acceleration in g here in this paper. DTPS data carries the unit of pressure in Pa. In order to seek how much pressure is due to the road profile and the axle accelerations respectively, one practical method is to use the transfer functions in the frequency domain. Based on the assumption above, linearity requires the equation in the frequency domain to be

$$Pdtps = HroadGr + AaxleGa \tag{3}$$

P_{dtps}, H_{road} and A_{axle} are the Fourier Transforms in the frequency domain of pressure from the DTPS of p_{dtps}, road profile of h_{road} and the axle acceleration of a_{axle} in the time domain, respectively. The transfer functions G_r and G_a relate the pressure changes due to road profile and axle acceleration respectively.

After rewriting the equation above, H_{road} can be obtained by the following equation

$$H_{road} = \frac{P_{dtps}}{G_r} - \frac{A_{axle}G_a}{G_r} \tag{4}$$

Let

$$G_1 = \frac{1}{G_r} \tag{5}$$

$$G_2 = -\frac{G_a}{G_r} \tag{6}$$

Substitute (5) and (6) into (4), then we have

$$Hroad = PdtpsG1 + AaxleG2 \tag{7}$$

Once H_{road} in the frequency domain is computed and an inverse Fourier Transform is applied to obtain the road profile in time domain

$$h_{road} = F^{-1}\{P_{dtps}G_1 + A_{axle}G_2\} \tag{8}$$

This equation means that the road profile may be estimated given the transfer function G_1 and G_2 as well as the measured time histories of the accelerations and the dynamic tire pressure. One conversion of the road profile from time domain to space domain is needed to be applied in order to evenly space the samples of the road profile before calculating IRI. The space interval depends on the classification of the accuracy of the IRI measurement (Sayers 1986). Once the road profile in space domain is found, it will be used as an input to the quarter model to estimate IRI using Eq. (1).

In order to compute the road profile h_{road}, the transfer functions G_1 and G_2 have to be measured ahead of field tests. Since G_1 and G_2 affect the data in both DTPS and the accelerations simultaneously while driving on the road, it is necessary to calibrate them one by one. Therefore, two calibration tests were conducted to obtain the transfer functions. One is a stationary test to calibrate the transfer function between the axle acceleration and dynamic tire pressure, G_a. The other one is a bar test to calibrate the transfer function between the road height and the pressure G_r. Then Eqs. (5) and (6) are used to calculate G_1 and G_2.

2.1 Stationary test

The purpose of this test is to find the transfer function G_a. The transfer function G_a means how much pressure change is due to the unit axle acceleration change. In order to independently obtain this part, the van has to be stationary in this test in order to avoid the effect from the road profile. Therefore the road profile of $h_{road} = 0$ is ensured. The frequency domain of the road profile is

$H_{road} = 0$ after Fourier Transform. Then using Equation (3)

$$Pdtps = 0 + AaxleGa \tag{9}$$

Once the dynamic tire pressure P_{dtps} and the axle acceleration A_{axle} are known at the same time due to the same excitation, G_a can be calculated. One stationary test was conducted which a person jumped on the rear of the van while data was collected by the accelerometer and DTPS. Data from DTPS and accelerometer was collected to record the associated response. Both types of data are collected in time domain as a_{axle} and p_{dtps}. A Fourier Transform is required to be applied to both data to convert to frequency domain. Then G_a is calibrated as

$$G_a = \frac{F\{p_{dtps}\}}{F\{a_{axle}\}} \tag{10}$$

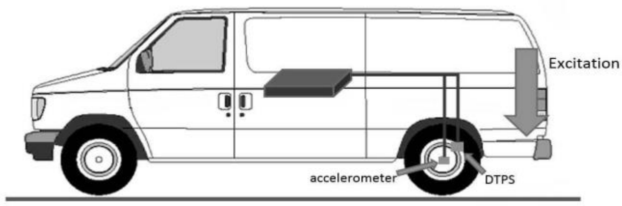


Fig. 5 Stationary test

This excitation was intended to simulate how much tire pressure change collected with DTPS is due to this axle vibration shown in Fig. 5 when only the body of the van vibrates and no other road factors are introduced. Transfer function G_a represents how much pressure change inside the tire is due to one g of vertical axle acceleration at each frequency.

2.2 Bar test

The purpose of this test is to find how much tire pressure change is due to the change of road profile. This will involve a driving test with axle acceleration embedded with the DTPS signals. However, after the transfer function G_a is obtained, substitute into (3) to obtain the transfer function G_r

$$G_r = \frac{p_{dtps} - A_{axle} G_a}{H_{road}} \tag{11}$$

The equation above indicates that once a road with known profile is available for this calibration test, the transfer function G_r can be obtained. Therefore, one bar test was designed and conducted to compute G_r. The road was selected from a flat, straight, new paved road. This road was approximated as a perfectly flat surface in the analysis. One customized wooden bar with trapezoidal cross-section was glued on the road surface considered as a defect shown in Fig. 6. Anywhere other than the trapezoidal wood bar is considered as the profile $h_{raod} = 0$. The transfer function G_r is calibrated using Eq. (11). Based on the assumption of the linear system, as long as the same vehicle is used to measure the road profile, any unknown road profile should be proportional to the height of the road profile in this bar test as a reference. Because the response should proportionally increase or decrease relative to the response to the customized bar. The dimension of the wood bar is known. When the van drives over this road, the dynamic tire pressure and the axle acceleration were collected, G_r was calculated together with the known road profile of the wooden bar.

The test was conducted at a constant speed of 40 mph. The customized trapezoid wood bar was 3.81 cm high, 4.28 cm wide. The width of the bar is bigger than the width of the tire to ensure the tire fully impact the bar. The bar is not sharp enough to break the tire wall when the tire hit the bar. However, the bar is also sharp enough to excite the response frequency band as broad as possible. From the frequency spectrum shown in Fig. 7, the settling time of the tire and the axle is 0.6 second when and after running over this bar. That means the suspension and the tire system has at least 0.6 second memory. The time window of the raw data of the DTPS and the axle acceleration in time domain should be selected at least 0.6 second to feed into the transfer function algorithm.

This length of time window will ensure no information loss during the signal processing.

The majority of the energy of the two signals is less than 200 Hz shown in Fig. 7. That means the frequency content less than 200 Hz is the most important part and the content beyond that frequency range is negligible.

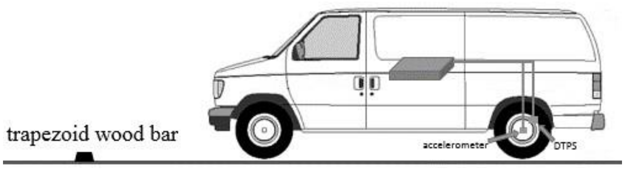
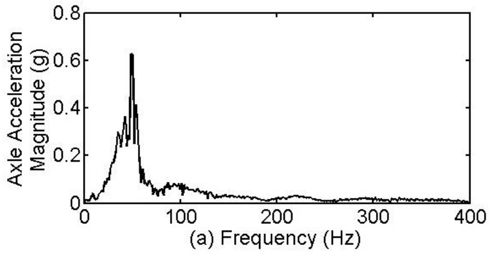
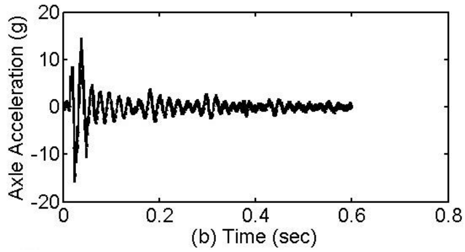


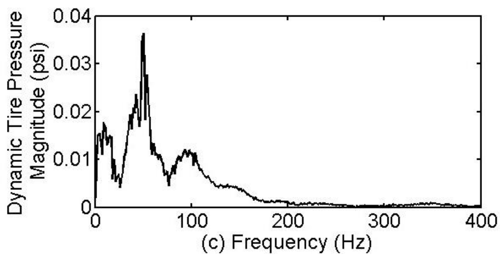
Fig. 6 Bar Test



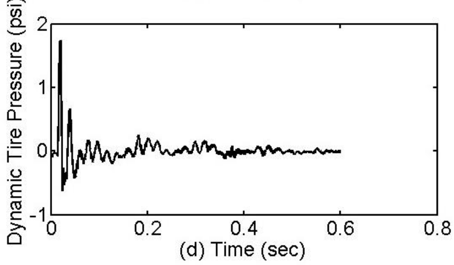
(a) acceleration in frequency domain



(b) acceleration in time domain



(c) dynamic tire pressure in frequency domain



(d) dynamic tire pressure in time domain

Fig. 7 Signal form accelerometer and DTPS in frequency domain and time domain

This also validates that the tire wall vibration here is not needed to be considered because of the mismatch of the frequency band between the two responses. From Figs. 7(a) and 7(c), the frequency content of the acceleration and the dynamic tire pressure have the similar frequency content around between 50 Hz and 100 Hz. That part proves that the mixing effects due to both the axle acceleration and the road profile exist in the DTPS data. That is also the reason why the transfer function G_a was calibrated prior to the bar test.

The pressure change due to axle acceleration is able to be subtracted from the total tire pressure change in order to obtain the road profile information. When driving over the wood bar, the tire also has a response below 50 Hz and around 100 Hz that axle acceleration does not have. That means the road profile excites the tire response but does not excites the axle vibration within that frequency band. By analyzing the DTPS data after subtracting the axle acceleration in frequency domain, road profile can be obtained from Eq. (8) in order to estimate IRI values of roads.

Another test was conducted over the wood bar at 40 mph over the same trapezoid wood bar using the calibrated transfer functions of G_a and G_r. This is the repeatability test of the validation of the transfer functions. The result should repeat because the configurations are the same as they were in the bar test. After passing this test, this whole setup can be put in service. The height of the wood bar is calculated as 3.75 cm using this transfer function method shown in Fig. 8. Compared to the actual height of 3.81 cm of the trapezoid wood bar, the error is 1.6%.

3. Field test

The purpose of this test is to validate the theory in practice in preparation for future service of road survey. One certification test was conducted in New Bedford Airport administered by the Massachusetts Department of Transportation (MassDOT). This test repeated surveying multiple times on the same road. This test is based on ASTM standard (E1926-08, 2008). Another field test was conducted in the city of Brockton, MA. The PCI values of each road were provided by a commercial engineering company using manual PCI survey based on ASTM standards (D6433-11, 2011) (D5340-11, 2011) (E2840-11, 2011).

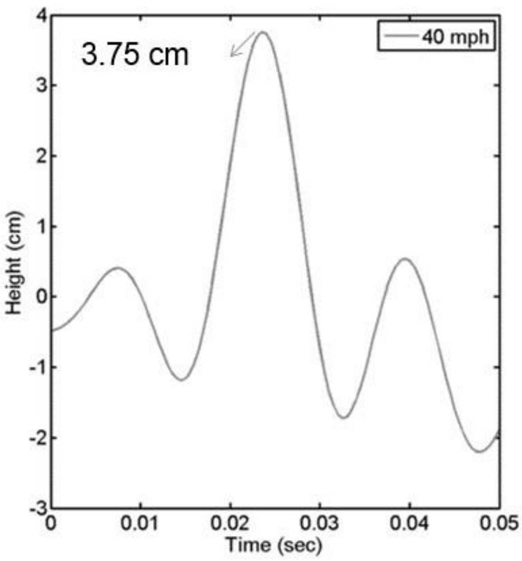


Fig. 8 Calibrated height measurement of the trapezoid wood bar

It took the company around 6 months to survey the whole city. For some long roads, some samples are randomly selected to represent the conditions of the whole roads rather than evaluate the conditions of those roads in whole length. This manual PCI survey may introduce some error as a reference. However, the DTPS data with the acceleration data was collected within 3 hours to survey 50 lane miles. Based on this speed, it will take the test van within a week to survey the whole city assuming 6 hours per day of surveying. And the IRI results can be calculated while driving with just up to 30 seconds delay. Since there are overlapping features of PCI measurement and IRI measurement and no IRI values were provided to city roads, PCI values of each road are used as a reference of road conditions.

3.1 Certification test

A certification test was conducted on an airport runway administered by the MassDOT. Contractors who want to survey IRI for the government have to pass this test. Multiple contractors using laser profilometers with accelerometers participated in this test along with our DTPS-based system. The official running speed is 72 km/h (45 mph). The start point and the end point were well controlled with a reflective tape. The system recognized the two locations by passing the tapes. Two wheel paths were drawn for drivers to drive along in order to best control the repeatability. This driving path was repeated ten times at this speed using DTPS based system in this certification test. The average and the standard deviation of the IRI value of this airport runway was 1.44 m/km (91.4 inch/mile) and 0.099 m/km (inch/mile) using DTPS with an axle accelerometer after driving repeatedly ten times, respectively. The ratio of standard deviation to average values is 6.8%. The average IRI value measured using DTPS system fell in the acceptable range of that measured using laser profilometers with accelerometers.

3.2 Urban road test

Twenty-two roads were surveyed in this test. Each road has two lanes. Three runs were repeatedly conducted for each lane of each road. The PCI values of each road ranges from 91 to 0 representing conditions from good to failed respectively according to the ASTM standard (D643311, 2011), (D5340-11, 2011), (E2840-11, 2011). These PCI values were predicted values based on the actually measured PCI values in 2006 using software Micro Paver 6.5. The predicted PCI values may have some errors compared to the actual conditions, but within the acceptable range. For example, the roads with the predicted PCI values of 12 and 7 should not have much difference in the actual condition since one is defined as "serious", an almost failed road and the other one is defined as a failed road. Details of road conditions for each road are given below. The symbol "X" in Table 2 means the data collected in that run was not valid due to technical reasons. They are not taken into the average IRI calculation of the whole road shown in Tables 1 and 2.

Table 1 IRI result of the certification test on a smooth road at different speeds

Speed (mph)	45	45	45	45	45	45	45	45	45	45	Average	Standard deviation
IRI (in/mile)	90.1	94.0	103.7	93.6	86.2	83.1	92.6	83.4	91.1	96.1	91.4	6.2
IRI (m/km)	1.42	1.48	1.64	1.48	1.36	1.31	1.46	1.32	1.44	1.52	1.45	0.099

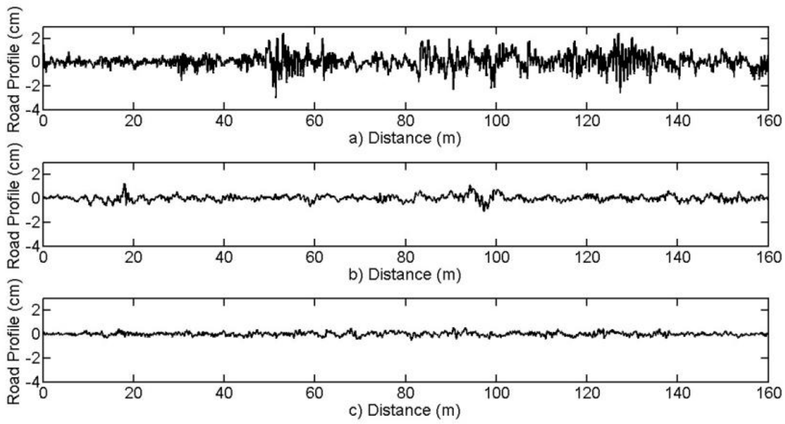


Fig. 9 Reconstructed road profile of 3 roads with different PCI values: (a) road profile of PCI = 7, (b) road profile of PCI = 64 and (c) road profile of PCI = 91

The images from Roads 2, 11, 13 and 19 in Table 3 have shadows due to the relative position to the sun. Work was not performed on the image processing to remove the shadows in this paper. The damage level in Roads 11 and Road 13 are medium among the six roads chosen from the 22 roads shown in Table 2. The estimated IRI values coincide with the PCI values, riders' feedbacks and images. The quality is in the middle between the above roads. The major defects of Road 11 and Road 13 are cracks shown from the images in Table 3. These cracks affect the PCI values and also IRI values of the two roads. It is visual that the cracks take up over 50% of the images. This density and the severity of cracks affects the tire response and captured by DTPS. That is why the IRI values of the road is higher than Road 1 and 2. However, the defects of cracks are better than patches and pot holes from Road 17 and Road 19, so the IRI values are less than those two roads.

Roads in good conditions are smooth and comfortable to drive on; however, roads in poor conditions are rough and bumpy to drive on due to road defects such as pot holes, rutting, patches, etc. The road profiles show clear difference between the good road and the poor road. Therefore, it is necessary to ensure that the road profile is distinguishable from different quality of roads since IRI is calculated from the road profile. The reconstructed road profile of the 3 roads with different PCI values is shown in Fig. 9. The three roads were selected from one good, one medium and one failed roads of the 22 roads above. It is clear that the roads with high PCI values are smooth because the magnitude and the variation of the magnitude of the reconstructed road profile is small shown in Fig. 9 (c)). Roads with low PCI values are rough shown in Fig. 9(a)). The magnitude and its variation of the medium road lie between the good and the failed roads shown in Fig. 9(b)).

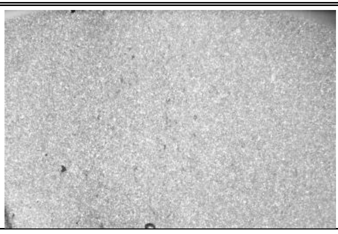
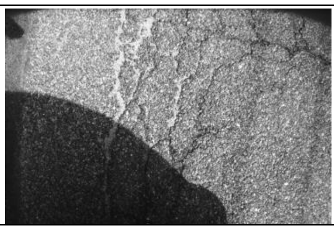
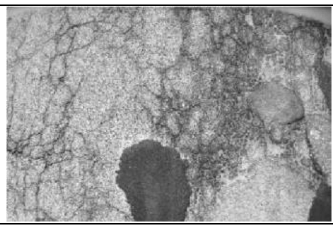
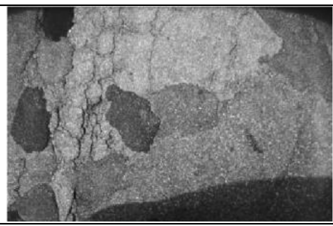
The estimated IRI values of each lane, each run from the 22 roads using the method described in the **2. Theory** section is shown in Table 2. The average IRI values for those roads reflect the overall quality of the associated road. In order to validate IRI values for all 22 roads, since true IRI values are unavailable, the following three sources of information were used: PCI values of the road, riders' feedbacks, and the images taken from the camera.

In addition, Road 1 and Road 2 have the low estimated IRI values of 2.6 m/km and 2.9 m/km and high PCI values of 91 and 90, respectively as shown in Table 2. According to the ASTM standard, riders should feel comfortable at speeds up to 100-120 km/h on the road with IRI within this range (E1926-08, 2008). The PCI values define these two roads in good condition (D6433-11, 2011), (D5340-11, 2011), (E284011, 2011). Besides, no defects were observed and small undulations were perceptual to riders on these two roads, which coincide with ASTM description as well. The associated typical representative images taken with the camera are shown in Table 3. It is visual that Road 1 and 2 are smooth. There is no defect at all on these two roads.

Table 2 Estimated IRI from Different Lanes of Multiple Roads with Different PCI Values

Road #	PCI value	Lane 1 IRI (m/km)			Lane 2 IRI (m/km)			Average IRI (m/km)
		Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	
1	91	2.8	2.4	2.7	2.4	2.7	2.8	2.6
2	90	1.9	2.8	3.1	2.8	3.3	2.5	2.9
3	84	3.3	3.3	3.6	3.4	X	2.7	3.3
4	77	6.9	6.7	7.6	6.0	6.6	X	6.8
5	76	4.7	3.6	4.2	5.5	5.6	6.3	5.0
6	74	2.9	2.9	2.7	2.0	2.8	X	2.7
7	72	5.6	4.9	4.9	4.5	4.3	3.8	4.5
8	67	6.6	7.9	7.1	6.6	6.7	6.8	7.0
9	66	5.0	6.8	7.1	6.1	6.8	X	6.4
10	64	5.1	6.2	X	4.6	4.4	4.7	5.0
11	64	4.9	4.0	3.6	5.8	5.0	5.9	4.3
12	63	5.9	5.0	4.7	4.8	5.4	5.2	5.0
13	55	7.6	8.6	8.5	6.8	7.1	7.5	6.7
14	41	6.2	5.1	6.2	6.4	X	7.6	6.4
15	32	8.8	8.6	10.5	11.2	10.5	10.5	10.4
16	13	7.5	8.9	8.3	7.1	6.1	7.0	7.5
17	12	12.1	11.0	12.4	10.2	9.9	8.8	9.3
18	8	9.5	10.0	9.0	8.7	X	8.0	9.0
19	7	11.3	9.4	9.3	9.8	11.9	11.3	9.5
20	2	12.5	12.7	12.5	X	12.3	10.8	12.2
21	0	9.9	9.9	9.0	8.0	8.0	9.0	8.8
22	0	10.6	10.2	10.6	12.0	10.3	11.4	10.9

Table 3 IRI Validation with the Reference to Sample Images of the Associated Roads Taken by the Camera

Typical image			
Road #	1	2	11
Typical image			
Road #	13	17	19

Road 17 and Road 19 have high IRI values of 9.3 m/km and 9.5 m/km but low PCI values of 12 and 7, respectively, shown in Table 1. According to the ASTM standard, it is necessary to reduce to the speed below 50 km/h and the road has many deep depressions, potholes (E1926-08, 2008), and PCI values define them in failed condition (D6433-11, 2011), (D5340-11, 2011), (E2840-11, 2011).

Riders in that test did drive below 50 km/h for safety reasons on those two roads. Based on riders' observation, there were a lot of potholes and patches on those two roads. The riders felt strong vibrations while driving over those two roads. The result coincides with ASTM description. The associated typical representative images taken with the camera are shown in Table 3. It was visually apparent during the test that Road 17 and Road 19 are two of the poorest roads. Big patches and pot holes are visible along the tire tracks. These defects caused significant tire pressure change. Therefore, the IRI values of these two roads are high.

The damage level in Roads 11 and Road 13 are medium among the six roads chosen from the 22 roads shown in Table 3. The estimated IRI values coincide with the PCI values, riders' feedbacks and images. The quality is in the middle between the above roads. The major defects of Road 11 and Road 13 are cracks shown from the images in Table 3. These cracks affect the PCI values and also IRI values of the two roads. It is visual that the cracks take up over 50% of the images. This density and the severity of cracks affects the tire response and captured by DTPS. That is why the IRI values of the road is higher than Road 1 and 2. However, the defects of cracks are better than patches and pot holes from Road 17 and Road 19, so the IRI values are less than those two roads.

The images from Roads 2, 11, 13 and 19 in Table 3 have shadows due to the relative position to the sun. Work was not performed on the image processing to remove the shadows in this paper.

The IRI values from Lanes 1 and 2 may be different for the same road in Table 2. That is because the roughness conditions are different for different lanes. Even for the same lane of the same road, the IRI values are a little different because the van could not practically drive on the exact same wheel path for all the three runs, especially driving around the city to complete so many roads within a certain amount of time. This effect is more obvious on roads with isolated defects. For example, if the tire hit defects in the first run but did not hit some of them in the other two runs on the same road, that may result in the IRI different values for the same lane of the same road such as Road 14, 15 and 17. Because if the tire did not hit defects on the road, there would not be significant tire pressure change, even though the driver was very careful and tried to drive along the same track for each run.

Road 3 to Road 7 have PCI values of 84, 77, 76, 74, and 72 respectively while their average IRI values are 3.3 m/km, 6.8 m/km, 5.0 m/km, 2.7 m/km, and 4.5 m/km respectively. The IRI values do not increase with the decrease of PCI values. From the PCI aspect, these five roads are defined as fair according to ASTM standard (D6433-11, 2011). These PCI values reflect an overall condition, but for different reasons. Some reasons may contribute to the IRI measurement as well. Roads with these reasons will have high IRI values such as Road 4, 5, and 7. Some reasons do not contribute to the IRI measurement, therefore, IRI values will not reflect the conditions that the PCI values assess. For example, Road 6 has PCI values of 74, but IRI values of 2.7 m/km. The IRI value is close to IRI values of road with PCI values 90 and 91. That is because the overall condition of the Road 6 is flat; however, the major defect of Road 6 is small longitudinal cracks that did not impact the tire while driving. Even though some of the cracks impacted the tire, they do not contribute to the long wave length road profile reconstruction since the gap of the crack is too small compared to the contact area between the tire and the road. The riders could not even feel the cracks while driving. This is another reason why PCI values are used only as a reference.

The poor roads such as Road 18 to Road 22 have severe defects everywhere such as patches, pot holes, and cracks. Even though the tire did not hit the same defect for the same run from the same road, it would hit other defects of the same or similar level. The total number of defects the tire hit may be the same or close so the IRI values were close to each other from different runs of different lanes.

The estimated IRI values have an approximately negative correlation with PCI values of the same road because they have overlapping road surface features taken into account. Both the low IRI values and the high PCI values indicate roads are good, and the high IRI values and the low PCI values indicate roads are poor based on the ASTM standard (E1926-08, 2008), (D6433-11, 2011) (D5340-11, 2011). Therefore, the general trend shows the negative correlation of the estimated IRI values with the respect to the predicted PCI values; however, the two indices reflect different aspects of the road features so the trend is not perfect linear. The dash line is the negative linear correlation in general; however, the two indices reflects different aspects of the road features so the trend is not a perfect negative correlation such as the roads with PCI values between 60 and 80. The estimated IRI values do not match the PCI values linearly. That is because the defects on those roads are not measurable for IRI measurement using either DTPS with an accelerometer or laser profilometers with accelerometers such as longitudinal cracks. The sensors do not capture the information, needless to say taking those into account of IRI measurement.

4. Conclusions

This paper has presented an approach to estimating IRI from a dynamic tire pressure sensor with an accelerometer attached to the rear driver's side tire and axle on a moving vehicle. This approach is able to measure IRI on urban roads. The approach assumes that the road profile is linearly related to axle acceleration and dynamic tire pressure in the frequency domain and the process proposes calibration tests for determining the appropriate transfer functions. Calibration tests were conducted to obtain the transfer functions between the body vibration of the vehicle and the tire pressure change and between the road profile and the tire pressure change. And a repeatability test was conducted before the system was put in service in the field. A certification test was conducted to test its repeatability in the New Bedford Airport administered by the MassDOT. In the certification test, the average IRI value was 1.44 m/km (91.4 in/mile) with standard deviation of 0.099 m/km. The ratio of standard deviation to mean IRI values is 6.8% for 10 times repeated runs at the speed of 45 mph. Since many cities use PCI values rather than IRI to assess road conditions and IRI and PCI measure road conditions from different aspects, they still have overlapping features. The IRI values measured using DTPS with an axle accelerometer is able to indirectly infer the PCI values of the roads. Another field test was conducted on a variety of road surface conditions in the city of Brockton, MA. Multiple runs on the same road were applied during the test. The results of estimated IRI values indicate that the data from DTPS with an axle accelerometer depends on the road roughness. Rough roads produce both high magnitude and variation of magnitude of road profile. Therefore, the IRI values are high. Smooth roads produce both small magnitude and variation of magnitude of road profile so the IRI values are low. The IRI values has a negative correlation with PCI values in general. This trend is also reasonable based on ASTM standards. So PCI values of each road are good references for the estimated IRI values. Moreover, the images taken with the camera and riders' feedbacks for each road also validate the estimated IRI values of each road. The advantages of this DTPS system are that a) the mounting setup is small; b) easy to install and remove from the vehicle; c) cost efficient; and d) the tire blocks ambient noises to simplify the signal processing procedure. Therefore, cities potentially could use this IRI measurement using DTPS with an axle accelerometer to access road conditions.

However, the limitations of this work are that: a) this method does not measure the exact profile, but a satisfied average profile over the tire footprint due to the tire/road interaction; and b) The roads where the vehicle suddenly accelerates or decelerates due to the stop sign, traffic light, or emergency brake are not involved in the calculation of the IRI measurement.

In general, the system of DTPS with an axle accelerometer has the potential to replace the current method of using profilometers and accelerometers to measure road profiles in order to estimate IRI. The combination of the DTPS and the accelerometer also have the potential to be embedded in the vehicles while manufacturing so as to form a network wide continuous health monitoring system of road ways based on IRI values.

Acknowledgments

This work was performed under the support of the U.S. Department of Commerce, National Institute of Standards and Technology, Technology Innovation Program, Cooperative Agreement Number 70NANB9H9012. The data analyzed in this paper was collected in the city of Brockton, MA. The authors gratefully acknowledge the support.

References

arrb. (2013), Retrieved from http://www.arrb.com.au/Equipment-services/Walking-Profiler-G2.aspx

ASCE, A.S. (2013), Report Card for America's Infrasturcture. Retrieved from http://www.infrastructurereportcard.org/

ASCE, A.S. (2009), Report Card for America's Infrasturcture. Retrieved from http://www.infrastructurereportcard.org/2009/sites/default/files/RC2009_full_report.pdf

Birken, R.S.C.F. (2014), "Implementation of a multi-modal mobile sensor system for surface and subsurface assessment of roadways", *Proceedings of the National Pavement Evaluation Conference*. Blackburg, VA.

Birken, R.W.F. (2012), "Framework for Continuous Network-Wide Health Monitoring of Roadways and Bridge Decks". *Transportation Systems Workshop*. Austin, Texas.

Board, T.R. (2004), National Cooperative Highway Research Program Synthesis 334. Washington D.C.: Transportation Research Board of the National Academies.

D5340-11, A. (2011), Standard Test Method Airport Pavement Condition Index Surveys. West Conshohocken, PA: American Society of Testing and Maerial.

D6433-11, A. (2011), Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys. West Conshohocken, PA: American Society of Testing and Material.

Dipstick. (2013), Retrieved from http://www.dipstick.com

dynatest. (2013), Retrieved from http://www.dynatest.com/equipment/functional/profiling

E1926-08, A. (2008), Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements. West Conshohocken, PA: American Society of Testing and Material.

E2840-11, A. (2011), Standard Practice for Pavement Condition Index Surveys for Interlocking Concrete Roads and Parking Lots. West Conshohocken, PA: American Society of Testing and Material.

FHWA. (2008). Status of the Nation's highways, bridges, and transit: conditions and performance report to congress. US DOT FHWA.

Gillespie T.D., Karamihas S.M., Kohn S.D. and Perera R.W. (1999), Operational Guidelines for Longitudinal Pavement Profile Measurement. University of Michigan Transportation Research Institute.

Infrastructure Management Services. (2012), Retrieved from http://www.ims-rst.com/data-collection.shtml

ISO13473-2.2002. (2002), Characterization of Pavement Texture by use of Surface Profiles - Part 2: Terminology and Basic requirements Related to Pavement Texture Profile Analysis. Geneva, Switzerland: International Organization for Standardization.

Karamihas, S.M., Gillespie, T.D., Kohn, S.D., Perera R.W. (1999), Guidelines for Longitudinal Pavement Profile Measurement. NCHRP Project 10-47.

National Climatic Data Center. (2012), Retrieved from National Oceanic and Atmospheric Administration: http://www.ncdc.noaa.gov/stormevents/choosedates.jsp?statefips=25%2CMASSACHUSETTS

Pacejka, H.B. (2005), Tire and Vehicle Dynamics 2nd Edtion. SAE International.

Roughness. (2012), Retrieved from http://www.pavementinteractive.org/article /roughness

Sandberg, U.A. (2002), Tyre/Road Noise: Reference Book, 97-167. Washington,D.C: Informax.

Sayers, M. (1995), On the Calculation of International Roughness Index from Longitudinal Road Profile. Transportation Research Record 1501, 1-12.

Sayers, M.W., Gillespie, T.D. and Paterson, W.D.O. (1986), Guidelines for Conducting and Calibrating Road Roughness Measurements. World Bank Technical Paper.

Texas Department of Transportation. (2012), Retrieved from http://onlinemanuals.txdot.gov/txdotmanuals/pdm/nondestructive_evaluation_of_pavement_functional_pr operties.htm

The Swedish National Road and Transport Research Institute. (2012), Retrieved from http://www.vti.se/en/vti-offers/on-road-measurement/measurement-of-road-surface/

TRB. (2004), National Cooperative Highway Research Program Synthesis 334. Washington D.C.: Transportation Research Board of the National Academies.

Ultra Technoloties. (2013), Retrieved from http://www.ultra-technologies.com/Pavement_Performance.html

Viatech. (2013), Retrieved from http://www.viatech.no/ezpublish-4.2.0/index.php/nor/Hjem/ViaPPS

Zhao, Y, Wu H.F., McDaniel J.G. and Wang, M.L. (2013), "Evaluating road surface conditions using tire generated noise", Proc. SPIE 9063, *Nondestructive Characterization for Composite Materials, Aerospace Engineering*, Civil Infrastructure, and Homeland Security. doi:10.1117/12.2045902

Zhao, Y., McDaniel, J.G. and Wang, M.L. (2013), "IRI estimation using probabilistic analysis of acoustic measurements". *Mater. Perform. Character.*, **2(**1), 1-21. doi:10.1520/MPC20130018. ISSN 2165-3992.

Zhao, Y., Wu, H.F., McDaniel J.G. and Wang M.L. (2014), "Evaluating road surface conditions using dynamic tire pressure sensor", Proc. SPIE 9063, *Nondestructive Characterization for Composite Materials*, Aerospace Engineering, Civil Infrastructure, and Homeland Security. doi:10.1117/12.2045902

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