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Using instrumented revenue vehicles to inspect track integrity and rolling stock performance in a passenger network during peak times

S.N.Lingamanai, C.Thompsona, N.Nadarajah*a, R. Ravitharana, H.Widyastutib, W.K.Chiu*c

a Institute of Railway Technology, Monash University, Melbourne 3800, Australia
b Centre Study of Transportation and Logistic, Institut Teknologi Sepuluh Nopember, Kota Surabaya, Jawa Timur, 60111, Indonesia
c Monash University, Mechanical and Aerospace Department, Melbourne 3800, Australia

Abstract

This paper discusses the use of Instrumented Revenue Vehicles (IRV), developed by Institute of Railway Technology at Monash University, to evaluate track condition and assess the dynamic performance of the rolling stock during peak operating hours in a passenger network in Indonesia between Lamongan and Surabaya. Assessment of track condition and the dynamic responses of the vehicle is crucial in setting safe operating speeds, in the development of economical proactive maintenance plans and maximizing throughput. The track condition and vehicle responses for this study were measured using accelerometers, spring nest displacement sensors and yaw, roll and pitch rate sensors. Sensors were strategically mounted on various locations of the wheelset, bogie and carriage to evaluate track condition, monitor load transmission and measure dynamic response of the in-service vehicle over multiple runs. The acquired data was analyzed and used to develop visual hot spot maps of the track to determine regions of high dynamic response. The acceleration measurements from the unsprung mass were used to evaluate the rail vertical profiles. This evaluation was carried out in frequency domain and the low frequency components were filtered out to remove contributions from long wavelength track features. A web based reporting system was used to provide plots and figures to communicate the results. Results presented demonstrate the ability of the IRV system to assess health conditions of track, identify regions of degradation and quantify the severity of the dynamic response.

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* Corresponding author. Tel: +61 4 3262 3038; fax: +61 3 990 51972.
E-mail address: Nithurshan.nadarajah@monash.edu
1. Introduction

Railway networks offer significant advantages for transport of passengers and freight as they occupy 2-3 times less land per passenger than other modes of road transport. Furthermore, the carbon footprint contribution of railway transport is significantly lower than road or other air transport [1]. The 2014 report by the Department of Infrastructure and Regional Development on the trend in Infrastructure and Transport, identified that the passenger kilometers on rail have a faster growth rate than both cars and buses [2]. Determination of structural health of track and rail vehicles is crucial to support this growth and ensure the safe and reliable operation of railways. Detrimental track conditions include heavy wear, corrugation, defective welds, formation failures and mud holes. These track irregularities may introduce erratic dynamic behavior in wagons that can impact on passenger comfort, increase wear rates, cause premature failure of rolling stock components and even increase the likelihood of derailment [3-7]. Identifying and addressing crucial track maintenance requirements can significantly increase the performance of the network, achieve safer network operation and reduce or prevent deterioration in the short and long term [8].

It is important to acknowledge the challenges in determining track degradation due to the complex nature of dynamic loading and variations in network utilization. The traditional solution in the industry has been the use of dedicated Track Geometry Cars (TGC). These dedicated monitoring vehicles are equipped with laser measurement systems, accelerometers, gyroscopes and other sophisticated sensors that allow them to identify and quantify a range of track issues such as alignment, curvature, rail profiles and twist. However, a key drawback in a dedicated TGC is that they are often very expensive, ranging in the order of millions of dollars, and they provide no direct indication of the dynamic behavior of the typical revenue vehicles. Since these vehicles often require exclusive track access, they are generally utilized infrequently (at a frequency of every three to six months) during non-traffic hours.

An alternative to the dedicated TGC is the use of wayside monitoring devices [9-10]. Wayside monitoring tools include Squeal Acoustic detectors, Wheel Impact Load detectors and Hunting detectors that help evaluate vehicle performance, identify defects and track degradation. However, these devices only evaluate the integrity of the rolling stock performance and track quality over a localized region of a track, thus making them an unfavorable choice to monitor significant sections of a network.

An alternative is the use of Instrumented Rail Vehicles (IRV) to help evaluate the track and dynamic characteristics of the rolling stock [11-12]. Such instrumented vehicles have been successfully implemented in various leading heavy haul railway operations by Monash University’s Institute of Railway Technology (IRT) [13-15] to evaluate track condition and monitor the dynamic performance of the rolling stock. This technology has helped to substantially reduce operational costs and increase network safety. IRVs are a fully automated measurement platform, which can be embedded on any in-service standard revenue vehicle. These vehicles are permanently equipped with advanced measuring systems such as differential GPS along with different types of sensors and logging units (refer to Fig. 1) to provide continuous feedback on track condition, vehicle dynamics and train operation [16-17]. Unlike dedicated TGCs, these instrumented vehicles reduce the need for track down time as the instrumentation is retrofitted to existing revenue vehicles. One of the key advantages of IRVs are that they allow the dynamic response of in-service rolling stock to be measured under typical operational loads. This provides information pertaining to the quality of the track condition. It has been recognized that the mode and severity of the dynamics response to a given track feature is often dependent on dynamic characteristics of the individual wagon. Armed with this information, plans can then be devised using the deterioration rates inferred from the dynamic rolling stock responses [18-21].

This paper presents a study on the use of IRVs to evaluate the track conditions and dynamic performance of a passenger vehicle in Indonesia along part of the rail network between Lamongan and Surabaya. The following sections detail the instrumentation, processing and evaluation of the track condition and vehicle performance along the newer north and the older south track towards Lamongan and Surabaya respectively.
2. Instrumentation

A passenger wagon, shown in Fig. 1 (a), was temporarily instrumented as part of this project in Surabaya Indonesia. The sensors were strategically mounted at various locations on the wagon to capture the dynamic behavior of the wheelset, bogie and carriage. Fig. 1 (a) shows the mounting locations used to measure the dynamic response of various components of the vehicle. All sensors were powered using the on board power supply available in the vehicle. Accelerometers were mounted on the wheel bearing housing to measure vertical acceleration. Measurements from these accelerometers on the unsprung mass were used to evaluate the rail vertical profile. Rail vertical profile is the surface geometry of the rails and may be used to detect damages and degree of degradation of the track. A total of 4 spring nest displacement sensors (SND) were used to measure the displacement of the front bogie with respect to the each end of the axle. Fig. 1 (b) shows an accelerometer mounted on the wheel bearing and a SND sensor mounted to measure relative motion between the wheelset and the bogie. This is used to determine the load transferred through the spring and the damper. Yaw and roll rate sensors were firmly secured to a cross bar on the bolster using mounting frames and adhesive, as shown in Fig. 1 (c), to help determine the Curvature and Superelevation. The bolster lateral acceleration was also measured using an accelerometer. The wagon responses were measured in all 6 degrees of freedom using accelerometers, and roll rate sensors attached to the under carriage of the wagon, as shown in Fig. 1 (d).

Data volume was managed by programming the data acquisition process to switch off when the train was stationary for prolonged periods. The recorded data was time aligned with the differential Global Positioning System (GPS) position, which allowed the geospatial location to be mapped to track chainage values. The instruments were in operation and collected data over 10 normal revenue runs of the train between Surabaya and Lamongan. The trips from Surabaya to Lamongan were along the north track and the return journey was along the south track. Raw sensor data files from the data logger were transmitted to the IRT facility in Monash University through the 4G telecommunications network. The signals acquired from all channels were resampled to 100 Hz to ensure a consistent sampling rate across all data sets for post processing purposes. In this paper the vertical accelerometers measurements from the wheel bearings and the body were used to assess the track quality and the dynamic responses of the vehicle during each of the runs.

![Fig. 1: Passenger wagon used for instrumentation](image-url)
3. Data Analysis and Visualization

As a first step, the severity of the dynamic response of the carriage were analyzed using tools developed by IRT [16, 18]. This was done by measuring the maximum vertical acceleration in 50m long sections of the track. Severity thresholds were set to classify the body responses at 3 levels, from 3 (least severe) to 1 (most severe), to assist with reactive and pro-active maintenance requirements. Fig. 2 shows the vertical carriage acceleration along the track over the 10 runs.

A heat map showing the track locations of severe body responses were developed using the measured dynamic responses of the rolling stock to identify where underlying track irregularities may be present. Fig. 3 shows a screenshot of an interactive dashboard that allows maintenance planners to interrogate the data and focus on track sections that may require maintenance and renewal. The condition of the tracks shown on Fig. 3 confirms the newer condition of the north track to Lamongan in comparison to the south track to Surabaya Pasar Turi. The web based reporting system developed by IRT has the capability of correlating the GPS position to a location on a map [19]. Thus closer spatial views of the map can be used to identify special features such as bridges, level crossings and turnouts along the track that excite the high dynamic responses.

Fig. 2: Body response severity along the tracks (a) North track (b) South track
The accelerometer measurements from the wheelsets were analyzed to assess the condition of the running surface. Fig. 34 and Fig. 5 show the peak acceleration measured with the accelerometer in the front right wheel, for every 50 m section of the track to Lamongan and Surabaya respectively. These results indicate that the newer North Track towards Lamongan has lower overall response values compared to those on the South Track towards Surabaya. These plots give a direct comparison of the track condition. When this type of data is collected on an ongoing basis, the degradation rate can then be determined by monitoring the track condition using IRVs over a period of time. A sample illustrating this is shown in Fig. 6. This information can be utilized to predict the track deterioration and hence plan for preventative maintenance interventions and services accordingly [20]. A preventive evidence based conditional maintenance strategy can significantly minimize transport disruption compared to a reactive maintenance approach [22-23]. Such maintenance strategies are highly favored especially in high utilization passenger networks where the availability of track for maintenance is extremely limited.
4. Rail Vertical Profile

The measurement of track geometry is critical to the identification of track defects and has long been used as a method of prioritizing maintenance activities. Dedicated TGCs commonly use a laser measurement system to map the rail vertical profile. The IRV determines the rail profile from the measurements recorded by the accelerometers on the unsprung mass. The acceleration can then be related to the displacement profile using integration schemes in the time and frequency domain as shown in Equations 1 and 2 [12] where \( x(t) \), \( \dot{x}(t) \) and \( f \) refer to the displacement profile, velocity profile and frequency respectively. Theoretically, the use of both equations should result in the same solution; however, some of the numerical schemes used for the integration can introduce small errors that accumulate. In this study the frequency based method was used, as it was found to have advantages over the time domain methods in conversion accuracy as well as flexibility of control [24]. When using this approach long wavelength features are avoided by removing the low frequency components in the signal. Long wavelength frequencies generally correspond to track design rather than track irregularities and degradation.

\[
x(t) = \int \ddot{x}(t) \, dt \tag{1}
\]
\[ \hat{x}(f) = \frac{\hat{\xi}(f)}{(i\pi f)^2} \]  

At low velocities of the train the accelerometer response to the track features is on the same order of magnitude as the noise floor. To account for this, a cut-off velocity of 30km/h was applied during this analysis, to remove all measurements during which the train was below the cut-off velocity. The track geometry was then calculated when speeds exceeded this cut-off value. Fig. 7 (a) and (b) show the rail vertical profile for both the north and south tracks respectively. In Fig. 7, the sections with missing information correspond to those regions in which the instrumented vehicle was travelling at speeds below 30km/h. It was observed that the rail vertical profile along the south track had a higher mean compared to the newer north track. The results from the calculated rail vertical profiles correlates well with the higher dynamic responses measured when the instrumented vehicle travelled along the south track.

Fig. 7: Right rail profile determined from the integration scheme (a) North track (b) South track

5. Conclusion

This paper examines the use of IRVs for track condition monitoring and related rolling stock performance under nominal operating conditions. The paper highlights the capability of the retrofitted instrumented vehicles to automatically monitor the track condition and vehicle responses without impacting on network operations. An integration scheme in the Fourier space was used to evaluate the rail vertical profile from accelerometer readings. The results obtained showed a good correlation between the measured dynamic behavior of the rolling stock and the measured track geometry, thus reinforcing the capability of the IRV system to both measure and predict track deterioration rates. The use of data visualization tools such as heat maps to summarize the condition of the entire track can assist maintenance planners and railway operators by allowing them to prioritize better schedule track maintenance.

6. Future Work

The next stage of the project will focus on the development of a vehicle model that can be used to determine the wagon response for a given track input. Two approaches are planned. For the first approach a grey box modelling will
be implemented where a mathematical model is developed from the knowledge of the system and its component interactions. The dynamic parameters pertaining to the model will then be estimated using the measured responses from this project as well as other similar measurements. The second approach will use a black box model that utilizes neural networks and machine learning to determine the complex relationships between the inputs and outputs. Both of these models can be used to predict the dynamic response of the vehicle for known track conditions. It is expected that the successful implementation of these approaches will substantially reduce both the Capital expenditure (CAPEX) and Operating expenses (OPEX) associated with running rail networks, while also improving overall safety.

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