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Dynamic on-board mass used for monitoring road condition and truck suspensions - Big Data from a widely distributed fleet of trucks

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Abstract

The last decade has seen a rapid expansion of on-board mass (OBM) measurement systems installed on heavy vehicles (HVs). This expansion has been for maximization of efficiency (i.e. loading to the legal limits but no more) and reducing the chance of being prosecuted for overloading.

With the increasing numbers of OBM systems within the HV fleet, the potential exists for their dynamic data to be gathered and used for monitoring both suspension and road degradation as a second emerging wave of functionality. This paper sets out early work in this variable-space and describes some "proof-of-concept" details of dynamic signals from an OBM-system-equipped HV (and data analysis of same) gathered as it drove on its normal routes. It is proposed that:

a) road degradation rates can be monitored with reporting back to road authorities for purposes of early road remediation after certain OBM signal thresholds of detected road damage are reached, and

b) HV suspension monitoring and analysis of wear trends (e.g. shock absorber) can be made available to HV operators using OBM systems reporting and monitoring.

1 Introduction

Traditionally on-board mass (OBM) measurement systems installed on HVs serve a dual purpose; (i) maximisation of efficiency by loading to the limit, (ii) reducing risk to the operator by greatly reducing the possibility of overloading and associated fines or penalties. Recently added to these has been improving compliance with legislative requirements such as "chain-of-responsibility" and "work health and safety" legislation when the OBM system is used properly. This paper proposes additional OBM system functionalities by using them to monitor HV suspension health and report road network asset condition.

A B-Double heavy vehicle (HV) had an on-board mass (OBM) measuring system installed for the usual reasons and the operator relied on this system as part of the everyday operation of the HV. Apart from the normal features however, the OBM system installed was different from the regular specification OBMs on the market; it also recorded dynamic data. These data were recorded as the HV travelled its normal routes with the data gathered cross-correlated with GPS readings as it did so. The resulting data-sets were gathered for some time.

This paper presents some preliminary analysis and results of those data sets. It also proposes that this early work is promising in terms of dynamic data informing two different sets of management: road authorities as well as HV operators.

It is proposed that: a) HV operators could be informed of the health or otherwise of the suspensions of their HV fleet and b) road authorities could be informed of the network degradation within their jurisdictions. Both of these outcomes by using measurements from OBM systems installed across a fleet of HVs. With GNSS (global navigation satellite system, incorrectly called GPS; GPS is the US system but GPS will be used in this report) monitoring and cross-referencing Big Data gathered from a distributed fleet of HVs, the state of the road network could be reported. Latency of the state of the road asset could be reduced to days with attendant efficiencies in scheduling asset repairs. The current installed base of the instrumented HV fleet provides basic on-board-mass data to the driver and GPS route data to the fleet operator. As we enter the age of the "Internet of Things" much more should be possible. This paper proposes a methodology to fill the gap between the "current state" of data reported from the HV fleet and a point where both accurate and current road network asset data is available. To date, no "Big Data" is being gathered from the (admittedly somewhat) instrumented HV fleet to provide road network asset condition data. Further, HV suspension data are not being reported at present in real time to the HV operator and this is also proposed.

1.1 Structure of this paper

This paper is structured in sections in the following manner:

Introduction; the structure of the paper and a description of each section of the contents are presented along with an overview of theory and brief literature review of the research and legislative requirements concerning HV suspension testing in Australia;

A description of each of the systems (e.g. OBM, GPS) used during the testing, including a description of the heavy vehicle and explanations of certain choices made in developing the test plan parameters for the experiment;

Procedures undertaken to gather the data from the testing;

Preliminary results from the data gathered during the testing showing some indicative plots of suspension responses to pavement unevenness;

Analysis of the results using the theoretical methods outlined in the Introduction;

A discussion section outlining the implications of the data presented and extrapolating a proposed framework for the use of multiple-agent data gathering (i.e. many HVs on the network) for both regulatory and business purposes;

Conclusions, presenting the next steps to take the proposals and "proof-of-concept" descriptions in the paper to an operational phase and outlining the potential benefits therefrom;

Acknowledgments, and

References.

1.2 Background

Karl, Davis, Cai *et al* (2009) showed that OBM systems available in Australia that measure static vehicle mass (i.e. HV stationary when measurement taken) were about 98% accurate at worst, and postulated that, with a bit of effort on the part of OBM manufacturers, 99% (or Class 1) accuracy would be achievable, allowing OBM system manufacturers to claim "legal for trade" status. Davis and Bunker (2007) presented summaries of the relationship between the measurement of HV mass and suspension data. Other work, particularly that of Davis (2010) and Davis and Sack (2004) showed "proofs-of-concept" that OBM systems could measure dynamic suspension data (i.e. record suspension signals as the HV travelled) used to determine suspension health. This due to the suspension signals being constrained fundamentally by the laws of physics governing the way the mass of the HV bounces during travel and predicting the movement of the HV's axle and body in accordance with the parameters of the HV's spring constants and the damping parameters of its shock absorbers. To date, no work has been done on using dynamic signals from HV suspensions to predict road network asset degradation save for that presented in this paper.

1.2.1 Suspension testing of heavy vehicles in Australia

As outlined by Davis and Bunker (2007) great strides forward were made in the field of HV suspension measurement from the 1970s to the 1990s. The Sweatman studies (Sweatman, 1976 & 1983) and those by de Pont (1999) and de Pont *et al* (1999), to name some, were collectively influential and seminal. These and other works set up the modern foundation for determining the relationship between dynamic loads in HV suspensions within the vehicle and also those loads onto the roads. It is for noting that, for instance, Sweatman's work included such experiments that were a) performed at slow speed (a quasi-static experiment in one case) or b) based on highway speed measurements from a single hub transducer mounted on a HV wheel; the signals from which were extrapolated to all wheels of each test suspension (for a number of suspensions) to give relative comparisons between suspensions for various dynamic loadings.

The Sweatman (1983) study proposed load sharing coefficient (LSC) and dynamic load coefficient (DLC) as performance measures for HV suspensions. Further, this testing estimated a function for road wear/damage related to suspension type and HV mass. The results appeared to be predicated on an assumption that dynamic load-sharing was present in the suspensions tested. The analysis of results seemed to assume that, for example; the dynamic load on the instrumented wheel added to that of its non-instrumented counterpart was the same as the total static load over those two wheels. That assumption relied on static behaviour being equivalent to dynamic behaviour and the two wheel loads being 180^0 to each other or undergoing "out-of-phase" vibration (Sweatman 1983). This analysis did not appear to take into account the possibility of both wheels bouncing either up or down at the same time (common mode or "in-phase" vibration).

More than 20 years later, Davis & Bunker (2009a and 2009b) proved the mathematical relationship between Sweatman's load sharing coefficient (LSC) and his dynamic load coefficient (DLC) in that these were inversely proportional to each other, thus casting doubt over the latter's importance given the disuse into which the former had fallen in terms of describing and characterising HV suspension dynamics. This is echoed by Lundström's reporting of Dr Cebon's questioning the importance of DLC as a measure (Lundström, 2007), for example.

In comparison to the foregoing, not much has been done this Millennium on HV dynamics as they relate to road damage. Any efforts expended this Century have been comparatively small compared with the great push forward at the end of the last; for example: de Pont (2004) is now over a decade old. That said, it needs to be acknowledged that those early research efforts were comparatively difficult when compared with the experimental tools and computing potential available today. This concept particularly highlighted by the comparison between the limited resources and technology to hand in the 1980s (say) compared with the mid-2000s where; for instance, the workhorse of the HV researcher's instrumentation: the accelerometer; is today cheap, reliable, accurate and as ubiquitous as (and indeed, installed in) smart phones.

1.2.2 VSB11

Today's HV suspension metrics contain provisions defined by Vehicle Standard Bulletin 11 (VSB11; Australia Department of Transport and Regional Services, 2004), as the basis for evaluating the suspension compliance of "road-friendly" suspension (RFS). VSB11 is a quasi-static test which extrapolates low-speed (or "fixed-in-place and drop") HV suspension test results to estimate road and bridge infrastructure damage of HVs operating at highway speeds. VSB11 mandates 2.0 Hz as the permitted suspension upper value for damped natural frequency and not less than 20% for the damping ratio value:

"The frequency of the sprung mass above the axle or axle group in a free transient vertical oscillation must not be higher than 2.0 Hz.

The mean damping ratio DM must be more than 20% of critical damping (Co) for the suspension in its normal operating condition" (Australia Department of Transport and Regional Services, 2004).

Noting that road damage and HV suspension testing experiments were limited by the technology at the time of writing VSB11, it is unfortunate that the assumptions around VSB11 were derived from the results of last Century's HV testing (described above). In short, VSB11 is limited to an experimental design constrained by technology dating from the last Millennium.

VSB11 also allows testing to be performed by a static drop test on a single axle suspension and the results of this test may then be extrapolated to HV behaviours at highway speeds and VSB11-compliant single axles installed in multi-axle suspension groups without further testing in those groups.

1.2.3 In-service HV suspension testing

It is for noting that VSB11 is a "type test" for new suspensions. Once the HV is placed into service, Australian road authorities do not require any comprehensively enforceable in-service suspension functionality test other than a voluntary maintenance regime which may or may not involve swapping out old shock absorbers (dampers) for new ones.

One of the suggestions examined for in-service compliance testing of HV dampers (Sweatman *et al* 2000) was to have HVs subjected to a test by a lift-and-drop machine, possibly placed at the side of the road. Fully loaded HVs were then to be lifted and dropped to check the damped natural frequency and damping ratio from the impulse loads thus generated. From this test it was proposed to determine whether the HV's suspension needed repairs. Another idea (Sweatman *et al* 2000) was that the vehicle was to be taken off the road with removal all of the shock absorbers, then have them sent out for a pass/fail test. If they passed, they were to be re-installed. Neither proposal gained industry or government acceptance (Starrs *et al* 2000); one of the factors for non-adoption was undoubtedly that the cost of labour to test a set of dampers was greater than a new set of dampers anyway.

It is for noting that Dr. Cebon, one of the authors of the Sweatman *et al* (2000) report, had already recommended an international system of parametric type-testing for "road friendliness" <u>combined with annual in-service testing</u> (Cebon, 1999). Others (Potter, Cebon, & Cole, 1997; Woodrooffe, 1995), agreed. Even earlier, the need to test new generation HVs for characteristics which contributed to their "road-friendliness" was recognised as "probable" (Woodrooffe, LeBlanc, & Papagiannakis, 1988).

What seems to have been missed in the rush forward to get RFS HVs on the roads in the late 1990s, under the various higher mass limits (HML) schemes and micro-economic reforms popular at the time, was that "road friendliness" is conditional upon suspensions being maintained. The ranking of suspensions "proved" that air suspensions were seemingly more "road friendly" than mechanical suspensions when new. The next issue was then how to maintain the HV suspension's "road friendliness" when the vehicle was placed into service. Codification of in-service road friendliness and enforceable testing for same was contained in each bilateral infrastructure funding agreement (BIFA) between the Australian Government and individually, the Qld Government and the NSW Government in 2005 (Australia Department of Transport and Regional Services 2005a & 2005b).

It has been estimated that infrastructure damage costs could be reduced by at least $59 million (in 2007 AUD) in Qld alone (Davis & Bunker, 2007) were testing of HV suspensions to ensure compliance with VSB11 carried out. That figure was determined from the Main Roads' documented cost of repairing infrastructure damaged by HVs that were, through lack of suspension maintenance, non-compliant with VSB11 (Davis & Bunker, 2007) factoring in the data that over 50% of HVs with air suspensions tested in 2006 failed at least one of the

VSB11 criteria (Blanksby 2006) resulting in greater HV wheel forces on pavements and bridges than should have otherwise been exerted by healthy (i.e. VSB11-compliant) HV suspensions.

In fairness, the Australian Government (Australia Department of Infrastructure and Regional Development, 2015) allows road authorities to conduct (amongst other activities) in-service suspension checks on HVs to determine compliance with VSB11 but, on balance, that approach does not contain the universality nor the rigour of the original BIFA proposals from 10 years ago.

To date, no cost-effective proposal for in-service HV suspension testing has received any sort of regulatory approval. This is in the context of NSW and Queensland gifting the transport industry a boon in that large lengths of NSW and Queensland road networks were opened to HML axle loads from 2005 (Australia Department of Transport and Regional Services 2005a & 2005b) in return for an assurance from the road transport industry that HV suspensions would be subject to enforceable in-service testing. Accordingly, the road authorities in NSW and Queensland gave the transport industry the ability to make more money, and (arguably) damage the roads more, from higher HV freight loads in return for a promise yet to be fulfilled 10 years later.

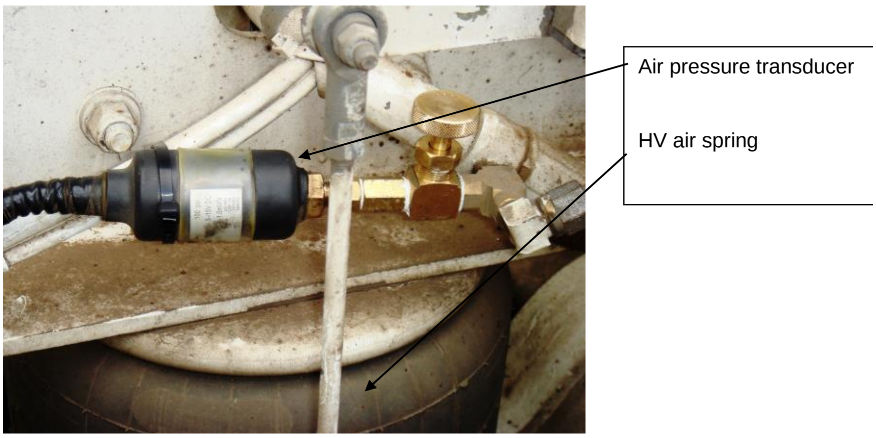
2 Systems, test procedures, results, analysis and discussion

2.1 OBM system and data capture

A modified CHEK-WAY® electronic weighing and data logging system running proprietary INS-COM® software was used on the test HV. The CHEK-WAY® system is subject to Australian Patent number 2004264997 and numerous international application numbers and patents which vary by country. With this system activated, it monitored dynamic air pressure in the air springs of each side of each axle group in real time.

The CHEK-WAY® INS-COM® software sample rate was 24ms as opposed to other OBM systems that had, in the past, processor update times of two or more minutes. Accordingly, the telemetry system sampling rate was 41.6Hz. It is for noting that higher frequencies such as axle hop were expected to be present in the order of 10 - 15 Hz (Cebon 1999). The choice of sampling frequency took this into account; the sampling frequency used by the CHEKWAY® system was therefore more than adequate to capture the test signal data since its signal sample rate was much greater than twice any axle-hop frequency. Accordingly the Nyquist sampling criterion (Shannon's theorem) was met (Houpis & Lamont, 1985).

Figure 1: Showing one of the air pressure transducers in relation to an air spring on the test HV



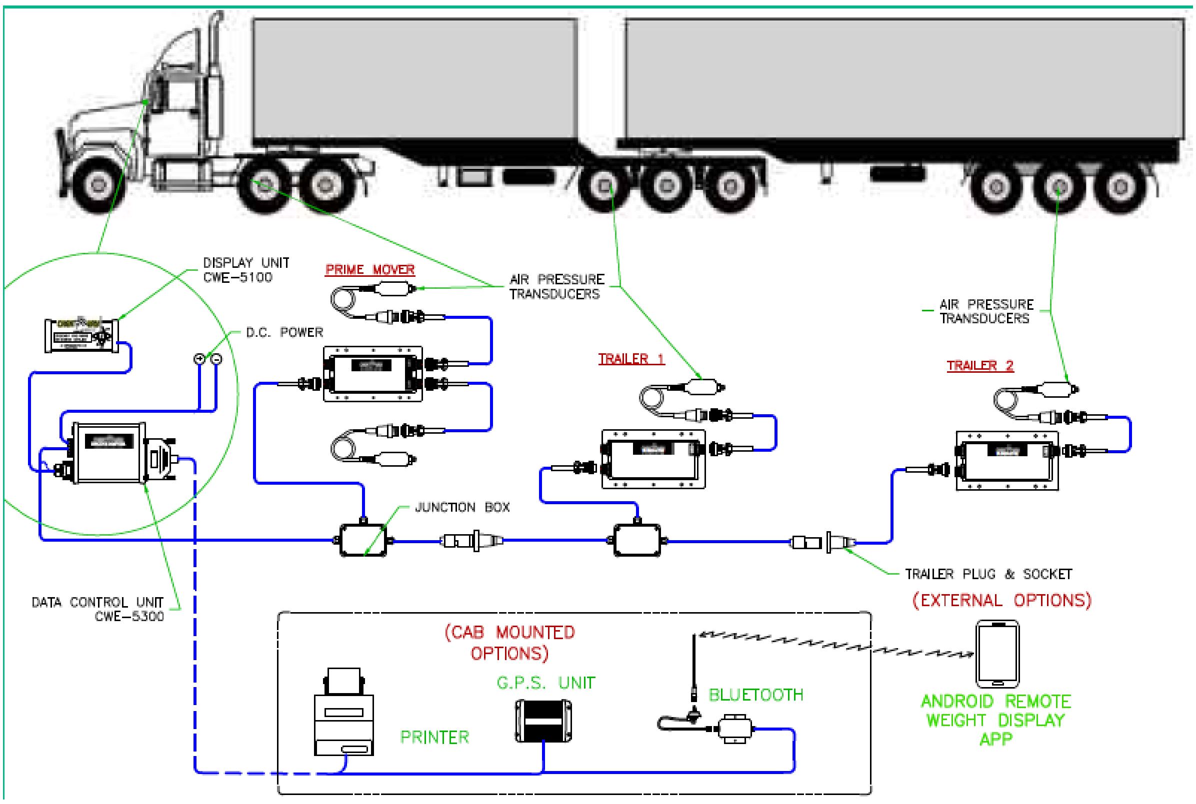
Air pressure transducers (APTs) were mounted in the air lines to the air springs as shown in Figure 1. The OBM system installed used the signals from these APTs to determine the pressure in the air springs when the HV was at rest and the OBM system computed this pressure into a total axle group mass signal after taking the unsprung masses such as the wheels, hub assemblies, axles, etc. into account. The APTs had a frequency response above 50Hz so that was adequate for the frequencies present in the air spring pressure signals.

Data were captured as the equipped HV travelled over normal uneven roads and bridges during its normal work day. The INS-COM® software used a version of the Fast Fourier Transform (FFT), reinvented in the 1960s (Cooley & Tukey, 1965) from an original idea by Gauss (Gauss 1866), to determine the damped natural frequency of the axle(s) being monitored. The data were sent back via the GPRS network. In an alternative embodiment, (not enabled for these tests) a DSRC depot-based RF device with the usual security protocols could have been used for downloading data.

Figure 2 shows the in-cab unit and readout, CHEK-WAY® system management computers and remote amplifiers that conditioned the APT signals installed in the test B-Double. The system management computers were used to manage the data capture timing and post-test data downloads. A schematic of the overall OBM system and how it relates to the HV for the tests is shown in Figure 3.

Figure 2: Readout and in-cab unit (LHS), system computer (middle) and remote amplifier (RHS) of OBM system

Figure 3: Schematic of the OBM system used for the testing



2.2 GPS

The test HV's routes were monitored by a GPS system (BR-355-S4 GPS receiver and a M1003GX704 GPRS modem) and the GPS co-ordinates were recorded as the HV undertook the operator's usual business.

2.3 The test vehicle

The test vehicle was one of the Rod Pilon B-Doubles as shown in Figure 4.

Figure 4: The test heavy vehicle; a B-Double

At the start of the testing period described in this paper, the original-equipment suspension manufacturer (BPW) tested all the shock absorbers fitted to the HV. BPW re-installed all dampers that tested as compliant with the original VSB11 specification. Two were faulty; these were replaced, thus returning the HV to its VSB11 factory-specified settings.

2.4 Data and parameters

The HV carried different masses per its normal operational requirements over the test period of January 2015 to May 2015. The signals from the APTs were recorded as described below. Some typical signals are shown in the figures below as recorded during the HV's everyday tasks.

2.5 Recording of data

The software was programmed to start recording when the instantaneous value of any APT signal rose to (say) greater than 20% of its averaged signal for the previous 10s. The system computers then retrieved the previous 2.0s of data and recording continued for another 8.0s providing a record of data for a total of 10s for that APT.

The threshold for recording start is programmable within the system used. 20% was chosen as the threshold value on the basis of some trial testing (not described here) which sought to balance the size of available memory against the magnitude of the "start" signal; thresholds significantly lower than 20% generated too much data and those of markedly greater values did not provide a sufficient number of triggers for the purposes of the testing.

To determine the component of the test HV's suspension degradation (as apart from the signals from degradation of pavement or bridge deck surfaces) contributing to the overall APT signal records, a "reference impulse" was used to characterise the HV's suspension. HV suspension parameters may be derived using an impulse function (Davis and Sack 2004; Davis 2010). Such a function was provided by the discontinuity between the pavement surface and the bridge abutment at the Wodonga Creek Bridge (Figures 5 and 8) which was traversed and the APT signals recorded from that movement in January 2015. The damping ratio derived from the exponentially decreasing APT signals (Figure 5) resulting from the impulse imparted to the axles was denoted the bounce response value (BRV).

2.6 Results and derived outputs

As described in 2.5, above, disturbances were detected (usually potholes or formative ones but also bridge abutments) as the HV performed its normal tasks. Figures 5 to 7 provide some representative samples measured at full load but many other signals were recorded at other loads, including at tare.

Figure 5: A typical APT signal for a smooth pavement approach to a bridge abutment and subsequent HV suspension interacting with bridge resonance

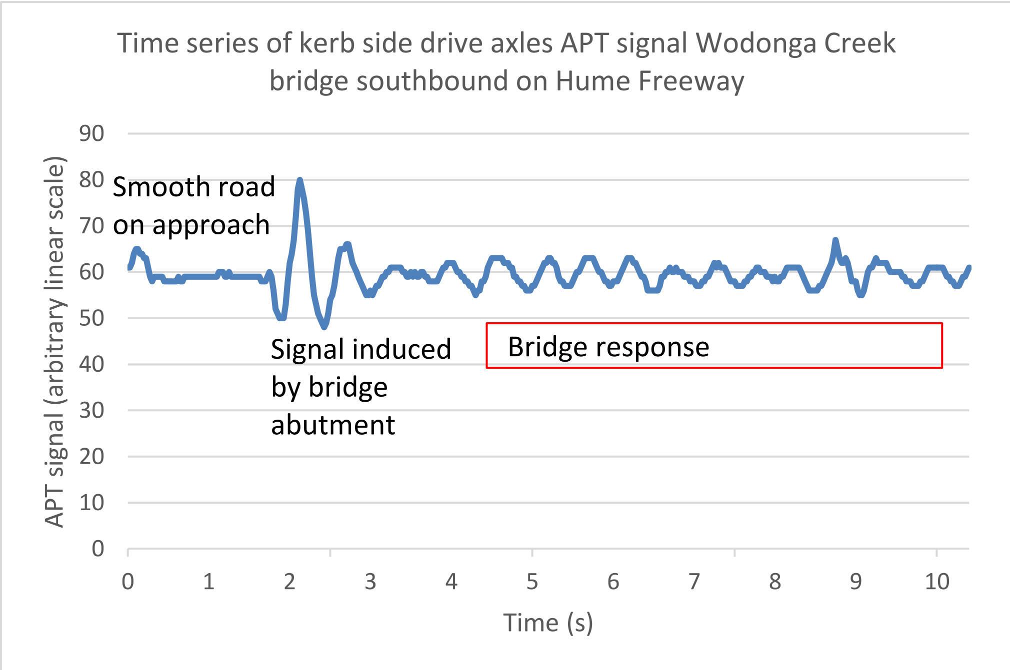


Figure 6: A typical APT signal for "normal" road roughness with small pothole

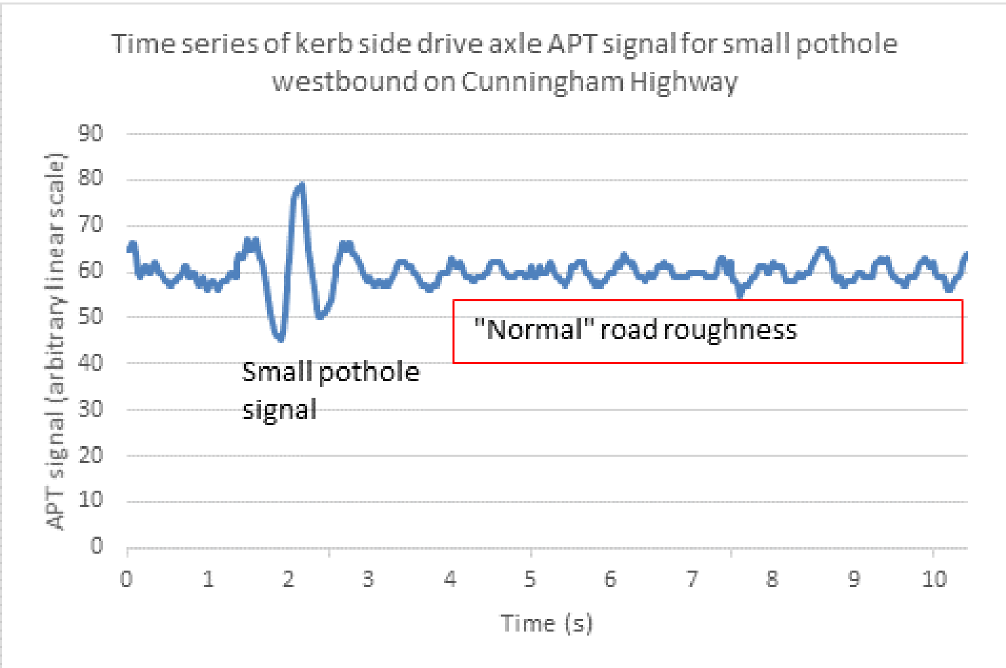
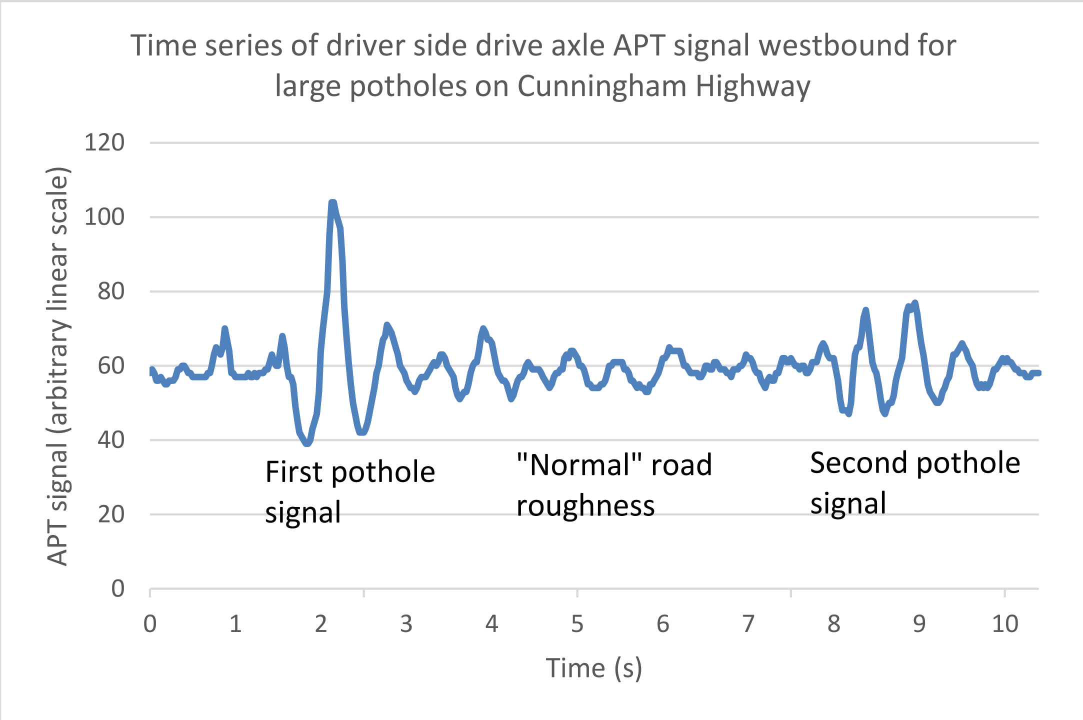


Figure 7: A typical APT signal for "normal" road roughness with two large potholes



The GPS co-ordinates recorded for the signals shown in Figures 5 to 7 were entered into Google Earth. The Google Earth images provided at the co-ordinates from the recordings taken at Figures 5 to 7 are shown in Figures 8 to 10. Figure 8 shows the northern Wodonga Creek bridge abutment going southbound.

Figure 8: The Wodonga Creek bridge looking south (ref: Figure 5) approaching abutment (courtesy: Google Earth)

Figures 9 and 10 show the Cunningham Highway pavement condition at the GPS locations recorded (i.e. as cross-correlated by the GPS and OBM systems synchronization at the positions) for the signals shown in Figures 6 & 7.

Figure 9: The Cunningham Highway looking east (ref: Figure 6) showing small potholes forming (courtesy: Google Earth)

Figure 10: The Cunningham Highway looking west (ref: Figure 7) showing series of larger potholes (courtesy: Google Earth)

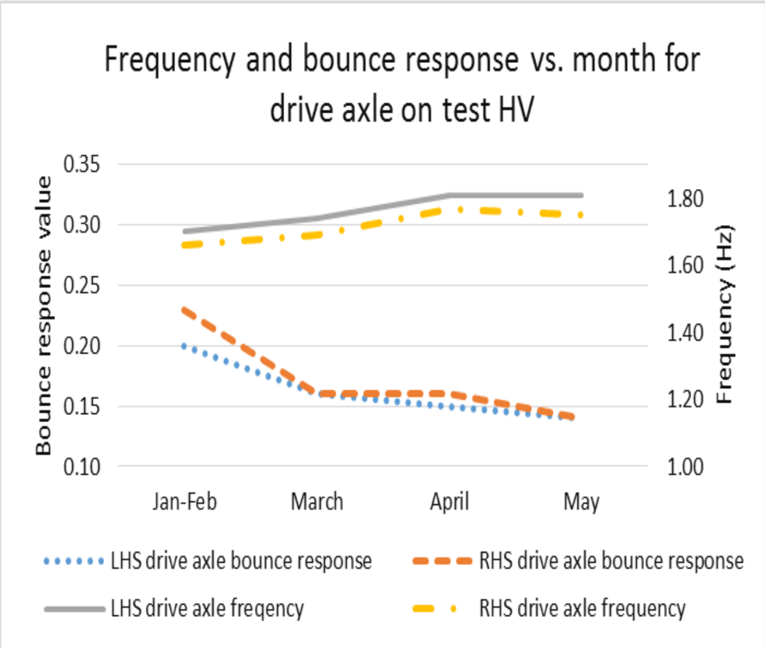
2.7 Analysis: suspension parameters – frequency and bounce response value

We will assume for the purposes of this paper that a bridge abutment impulse is a constant input to the HV suspension at that point on the network at highway speed and at full load. Obviously speed, group load and other variables such as slight movement of the bridge abutment over many years will affect this response but for the purposes of a preliminary argument, let us assume this consistency; with more data in the future, more refined analysis will be available. Figure 5 shows an exponentially decaying time-series suspension response arising from the input into the HV suspension from the Wodonga Creek bridge abutment with the HV travelling at 97.6 km/h and at full load. (Indeed Figures 5 to 7 show this exponentially decaying response to all examples of disturbances encountered in the road surfaces). We have termed the in-service measured damping ratio (Davis 2010) from a non- or very slowly-moving road disturbance feature, such as a bridge abutment, the bounce response value or BRV. For the VSB11-compliant dampers installed on the test HV, the BRVs for the Wodonga Creek Bridge abutment impulse were 0.18 and 0.19 for the driver side and kerb side drive wheels respectively. This correlates well with the requirement for bench-tested "road-friendly" HV suspensions to have a damping ratio of at least 0.20. The damped natural frequency was determined to be 1.79Hz and 1.98Hz for the driver side and kerb side drive wheels respectively as outlined in 2.1 above and in Davis (2010); showing field compliance with VSB11 in the frequency domain.

Having confidence in the BRV as a "proof-of-concept" for Wodonga Creek Bridge, the Biddon Creek Bridge on the Newell Highway (a route more frequently-travelled by the HV) was then selected for analysis. For multiple passes at the same speed and at full loads, the BRV and damped natural frequency values for the test HV's drive axle group were plotted for the period Jan to May 2015 as shown in Figure 11 for this network feature. The damped natural frequency of any axle was able to be determined using the Fast-Fourier Transform contained in the INS-COM® software where the damped natural frequency of the axle(s) concerned was determined as the frequency of the signals (such as those shown as the suspension responded to "first disturbance" or "first pothole" in Figures 5 to 7) from the recorded data. Extensive use of this technique has been documented previously including Davis (2010) and Davis and Sack (2004). It is a standard technique for extracting frequency data from time series data using the techniques first outlined by Gauss (1866) and applied by many other researchers (Davis and Bunker 2007).

It may be seen that the locus of the damped natural frequency increased and the locus of the BRV decreased for the test HV's suspension over the test period. This indicated suspension wear when compared with the requirements of VSB11.

Figure 11: Frequency and bounce response values of the drive axle at the same point on the network at full load.



2.8 Discussion

2.8.1 Suspension health check

Suspension manufacturers' recommendations vary but typical advice for damper replacement is 300,000 to 500,000km for a complete rebuild of the suspension (including spring eye bushes, new shock absorbers and wear pads, if fitted). The problem with these recommendations is their arbitrary nature and the fact that, like imported HV suspensions, they originate from countries where group loads and road conditions vary from those in Australia.

The BRV and damped natural frequency data available from the “proof-of-concept” tests herein are the test HV’s interaction with the bridge asset. Were this to be expanded across the network with cross-correlation of the HV’s GPS position with the frequency and BRV data, an operator would be able to see a time series (for example, Figure 11) of the HV’s suspension response at the same place on the network with the same load. It will, in all likelihood, be seen from that data for the same HV group mass, speed and point on the network, the BRV will show a temporal degradation of these signal values as a response to an impulse function (that is, traversing a bridge abutment) and the damped natural frequency increasing over time. At least two factors will be at work to generate the change in these values over time. One will be the bridge abutment moving with traffic (time constant: years) and the second (much faster) will be suspension damper wear (time constant: months; Figure 11).

Davis (2010) showed that adequate correlation could be found between the manufacturer’s VSB11-certified HV suspension damping ratios and those found by running a number of HVs over field disturbances. He proposed a pass/fail test based on field data obtained from HV suspension tests where, were the damping ratio from such field tests to drop below some arbitrary value (proposed here as say, 0.1), the dampers could be renewed by the operator. It is noted that the damped natural frequency for HV suspensions is not affected overly whether measured in the VSB11 environment or in the field. Extrapolating from the plots in Figure 11 and using the “field measurement” criterion of not less than 0.1 for BRV and the VSB11 damped natural frequency of not more than 2.0 Hz; the dampers on the test HV will need to be checked some time after July-August 2015 (this paper was submitted in early June 2015).

Were the reduction in BRV values available to the operator using an OBM system as described, once the BRV reached an arbitrary lower threshold, the suspension dampers could be replaced without further testing but on the assurance that they had reached a level of dysfunction that warranted replacement. This due to the monitoring of the relationship between road and vehicle response in real time and over a period. This could mean a saving of over $5,000 to $10,000 in maintenance of a B-Double or an A Double (Type 1 road train) over a 2-3 year period. In addition, the HV would not need to come off the road for damper testing that may merely prove that no action is required. In addition, timely replacement of shock absorbers (dampers) would increase road safety since damper failures “in the field”, resulting in hydraulic oil spilt on the road, would be reduced with the potential for skidding as well as pollution reduced[1] accordingly.

2.8.2 Big Data from a HV swarm

At present, road network assets (such as bridges) are checked manually by inspectors visiting each site and evaluating the asset’s condition or the asset (such as pavement) is recorded using vehicle-mounted video cameras and data are post-processed in the back-offices of the road authorities in Australia. These procedures contain an inherent latency (delay) between any asset degradation and the inspection process since not all of the network can be measured at once by ever-reducing numbers of road authority staff. However, there is a more novel way to gather asset data, particularly early onset of asset degradation and development of multiple reporting (therefore greatly increasing certainty of condition reporting).

[1] The reader is invited to view the effects of oil pollution at the following link: http://www.harvestingrainwater.com/wp-content/uploads/2011/07/HCP-IQ-Test_with_credits_SHORT.pdf

Signals such as those shown in Figures 5 to 7 at known masses, speeds and GPS locations via the communications links described herein above could be used to inform bridge and pavement asset managers of the state of their assets. Assuming data supply arrangements were in place between asset managers and HV operators, this information from a distributed fleet of HVs would allow asset managers to know what is the current condition of their assets in real time; the only latency being the time to get the data from the truck to the back-office or road authority. Further, impact loads on all sections of the road network would be able to be estimated and degradation over time plotted. Where the need for a minor repair or upgrade may be missed in the current approach of asset inspections due its inherent delays or human error, it would be apparent with the data provided from a "swarm" of HVs on the network going about their normal activity. Further, one developing asset failure may or may not be missed by any system but with multiple reports of the same asset failure at the same point on the network by multiple HVs, the probability of error or lacuna in determining asset failure would be greatly reduced.

It is acknowledged that the proposal here relies on trucks being on the roads in question. An argument could be mounted on the basis that the proposed approach would only monitor those assets on heavy vehicle routes. However, asset failures are more likely to occur on exactly those routes; heavy vehicles are the majority reason that pavements and bridges wear. Even the most favourable pavement engineering "power rule" (Davis 2010) approach indicates that the damage to road assets from HV axle passes is somewhere between 6 and 2000 times more destructive than an average passenger car. Further, light trucks travel passenger-vehicle routes delivering to local supermarkets, shops, etc. These vehicles are increasingly fitted with OBM system for the same compliance reasons outlined in the Introduction. There is no reason why these light commercial vehicles could not also be included in a monitoring regime as outlined in this paper.

The approach of multiple reporting and earlier provision of minor degradation data for assets would enable a more timely approach to repairs before condition degraded further; costs for sooner remediation would be less than to rectify more degradation later. Every time a pavement or bridge is repaired, diesel fuel is used to power the repair equipment. Bitumen or asphalt is required to rectify the road network asset and manufacturing these compounds emits greenhouse gasses as do the repair machines. The larger the asset degradation, the greater the repair emissions become. Smaller, timelier and pro-active pavement sealing before moisture reached the sub-base and caused larger failures (thus extending asset life) would result in reductions in greenhouse gas emissions. It is not possible in the scope of this paper to quantify this reduction but it should be something that could be quantified and reported should the monitoring system proposed herein be implemented.

We propose a "swarm" of HVs with suitable OBM and data logging systems described above monitoring the road network in real time. Incremental operating costs should be negligible since OBM system data would be generated from normal HV operations. By detecting increases in suspension signals due to road irregularities, these types of OBM systems could become the "canary in the coal mine" to pinpoint asset degradation in time-frames that would be virtually instantaneous compared with current practices. This would improve road safety, reduce longer-term rectification costs by prompting early intervention and reduce reliance on current inspection regimes with their asset condition reporting latency.

3. Conclusions

3.1 Suspension health check

This paper proposes a "proof-of-concept" low-cost method for determining HV suspension health integrated within a larger functionality for road asset monitoring. It does not propose that VSB11 be superseded or that the certification of new suspensions is invalid; merely that in-service HV health measurement becomes possible in a comparative (not absolute) framework so that operators can choose a threshold of suspension damping below which they can schedule maintenance for their vehicles at a convenient time. Timely replacement of shock absorbers also increases road safety by reducing the likelihood of on-road damper failures spilling hydraulic oil on the road with an attendant reduction in pollution.

3.2 Big Data for asset monitoring from a HV swarm

This paper also proposes a “proof-of-concept” method for detecting parts of the road network that can be targeted for early remediation of assets. Road authorities would benefit from asset condition data gathered from a distributed collection process (e.g. a multitude of OBM-equipped HVs) generating “Big Data” in order to take timely action to curtail pavement and bridge asset damage before it becomes too great.

Another (yet-to-be quantified) benefit arising from the approach outlined herein is greenhouse gas emission reduction by allowing smaller, targeted and timelier road repairs by road authorities. This would increase safety for all road users, in that pavements would be better maintained.

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