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REDUCING WHOLE BODY VIBRATION LEVELS IN OFF-ROAD, HEAVY-DUTY VEHICLES: A CASE STUDY WITH COMPUTER MODELLING

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ABSTRACT

This paper describes a case study involving the dynamic ride performance of a 30-ton, articulated dumper vehicle. The vehicle in question was originally fitted with a front-end, solid axle with leading arm mechanism. After an engineering design program, the vehicle was custom-fitted with a Timoney Independent suspension system. Extensive testing and modelling activities using LMS Virtual.lab Motion® were undertaken to determine the productivity levels of each vehicle. It was demonstrated that the vehicle fitted with a Timoney suspension could achieve a productivity increase of up to 50%. A health analysis is also presented which shows the Timoney Independent suspension system reduces the potential health risk.

Keywords: Whole Body Vibrations, Independent Suspension

1 INTRODUCTION TO HUMAN VIBRATION EXPOSURE

Humans who are at an interface with machinery are often exposed to mechanical vibrations or shock loads. In the simplest case, a person who is manually controlling a powered machine or hand tool experiences hand-transmitted vibrations. In the case of vehicular transportation, the operator and passengers will experience whole-body vibrations [1,2]. A human's exposure to vibrations must be limited due to comfort and health reasons. Griffin [1] catalogues many of the ailments that can result from over exposure to mechanical vibrations. The whole-body vibrations are transmitted to the person where contact is made with the machine, via the floor and/or the seat cradle (depending on the posture of the individual: standing, seated, or supine). The International Organization for Standardization provides the standard on testing and evaluating human exposure to whole-body vibrations and states the frequency range of interest to be 0.5 Hz to 80 Hz [3]. Air-borne vibrations, i.e., acoustics, are not considered in whole-body vibration analysis.

The Official Journal of the European Communities provides directive 2002/44/EC of the European Parliament on the minimum health and safety requirements regarding the exposure of workers to the risks arising from vibration [4]. This directive outlines the daily exposure action value and the daily exposure limit value (these levels of exposure must be calculated using the method outlined in [3]). The Root Mean Square (RMS) acceleration limit value when standardised to an eight-hour reference period is 1.15 m/s^2. When converted to an equivalent vibration dose value (eVDV), the limit is 21 $m/s^{1.75}$. Employers must ensure that workers are not exposed to vibration levels above the daily limit value. The daily exposure action level (RMS acceleration) standardised to an eight-hour reference period is 0.5 m/s^2. The equivalent vibration dose value (eVDV) to reach the action level is 9.1 $m/s^{1.75}$. If workers are exposed to vibration levels higher than the action level, then the employer must take action to reduce the employee's exposure to the vibration.

2 EXPOSURE TO VIBRATION ONBOARD GROUND VEHICLES

Mechanical vibrations occur in every ground transportation vehicle, whether they are used for on-road or off-road activities. Vibrations may occur due to moving or rotating parts within the vehicle, for example, the engine driveline. These vibrations are typically periodic or cyclical and do not contribute significantly to whole-body vibration levels. The most significant contributor to whole-body vibration comes from the excitation at the road-wheel-to-ground interface, that is, at the tyre contact patches. As a vehicle drives over terrain, forces are continuously generated at the tyres' contact patches. These forces are random in nature and cause excitation or vibration that is transmitted through the tyres, the suspension system, the chassis, the seat, and to the human occupant. The occupant experiences vibrations occurring in all six degrees of freedom: vertical, lateral, and longitudinal translations; and roll, pitch, and yaw rotations. The ISO standard [3] considers contributions from all six degrees of freedom.

Naturally, off-road vehicles experience high levels of random vibrations due to the uneven nature of the terrain. The random vibrations have a wider spectral content than a periodic vibration [5].

2.1 Vehicle Suspension Systems

The suspension system on a vehicle improves the mobility and comfort level, especially in off-road conditions. The role of the suspension is to isolate the chassis and its occupants from the harsh loads generated at the tyre while driving. The suspension system absorbs and dissipates the vibration energy arising from the ground interaction using a mechanism of springs and dampers. The suspension system is typically tuned to permit acceptable frequencies (in the range of 0.5 to 1.3 Hz) and to suppress the vibrations at harmful higher frequency ranges. The vehicle's ability to traverse terrain comfortably is often called the vehicle's ride quality [6].

Solid Axle Suspension Systems

Some heavy-duty vehicles have solid-axle suspension systems, which are sometimes also known as beam-axle systems. In this configuration the opposing wheels on the axle are bolted directly onto a shared solid axle. Hence, the wheel motions are strongly coupled to each other by the motion of the axle. This type of axle system will have a suspension mechanism between the main chassis and the solid axle. The mechanism characterises the degrees of freedom between the main chassis and the axle and hence the wheel motion.

Independent Suspension System

An independent suspension system is one where the opposing wheels on a given axle are uncoupled from each other. Each wheel station on the axle has its own suspension system mechanism that allows the wheels to move with an independent degree of freedom into bump and rebound positions. Strictly speaking, the only connection between opposite wheel stations is through the suspension to the main chassis frame; however, where necessary, some independent suspension systems have a flexible anti-roll bar connected between them to improve handling. We do not consider anti-roll bars in this manuscript. Independent suspension systems are regarded as giving better ride performance than their solid axle counterparts. Reasons often quoted for this improvement are reduced unsprung mass and improved wheel travel.

Timoney Technology is an Irish company who is a leading provider of independent suspension systems for heavy-duty machinery worldwide.

3 WHOLE-BODY VIBRATIONS: A CASE STUDY IN CONSTRUCTION EQUIPMENT

Timoney Technology was requested by a customer to analyse and improve the ride performance of a commercially-available, 30-ton, articulating dumper vehicle – the type of vehicle used for road construction and quarry projects. This type of vehicle configuration has a tractor and a trailer unit that are connected by an articulating joint. The articulating joint allows the tractor and trailer to rotate along their longitudinal axes relative to each other. The articulating joint mechanism also provides the steering action of the vehicle. The tractor unit of the vehicle in question had a solid axle on a leading arm suspension mechanism.

The ride performance of such a vehicle is significant because of the impact it has on the productivity of the vehicle. A vehicle's productivity is defined for a prescribed haulage circuit or route and it is given as the tonnage of payload material hauled per hour. If the vehicle can complete the haul circuit at higher speeds then the productivity increases. Furthermore, a machine performance metric, M, may be calculated using the hourly cost of owning and operating the vehicle (Euros/hour) and the productivity (tons/hour).

$$M = \frac{HourlyCost}{Productivity} \tag{1}$$

The machine performance metric is given in units of Euros/ton.

To improve the ride performance by reducing the whole-body vibration exposure, Timoney Technology proposed an independent suspension system for the front axle on the tractor unit. A driven-axle, double-wishbone, independent suspension system was designed and installed to the vehicle.

3.1 Initial Testing and Modelling

Quarry Floor Tests

During the development phase of the project, each vehicle (solid axle and independent suspension versions) was instrumented with accelerometers on the driver's seat and tested on a quarry surface representative of typical operating conditions for this class of vehicle. The vehicles were driven over typical construction and quarry road surfaces at constant speeds. The ISO standard [3] was applied to the test results and comparisons were made between the ride index values. The ride index is calculated using the measured RMS accelerations, the root sum of squares, and weighted filters as described in [3]. The ride index has units of m/s^2. The vehicles were tested at both laden and unladen conditions. The driver of the vehicle maintained the speed at constant levels so that comparisons could be made. It was found that the vehicle with independent suspension performed consistently better than the vehicle with the solid axle. On a quarry loop section of the terrain, the independent suspension performed with a 51% improvement in ride index (that is, a lower ride index) when laden and a 47% improvement when unladen. Across the quarry floor section of the terrain, the independent suspension performed with a 28% improvement when laden and 19% improvement when unladen.

Modelling Activity

Detailed computer models of the complete vehicles with solid axle and independent suspension were developed using LMS virtual.lab motion®. This type of modelling considers the components in the vehicle as rigid bodies with defined linkages between components. Spring and damper elements provided the suspension effects and tyre models were available within the software package. Random road profiles were generated and used in the model. The spectral content of the random roads followed guidelines set out in [5]. Left and right tracks with coherence were generated for each road profile.

Modelling results were compared to the experimental measurements from the quarry testing and after detailed deliberation the model (beyond the scope of this paper) was deemed to be fit for purpose.

3.2 Comparative Analysis Methodology

Once confidence was gained in the modelling technique, a comparative analysis was conducted to determine the improvements that could be expected in productivity and machine performance. Construction plant tyre manufacturers distinguish three levels of construction site application: low, medium, and high. We may expand upon the description of the applications and the expected outcome on tyre life.

Low applications:

- Earthmoving and stockpile applications.
- Medium to long hauls on well-maintained haul roads and dirt tracks.
- Almost all the tires wear through the tread from abrasion.

Medium Applications:

- Short to medium length haul routes, ranging from well-maintained haul roads to loose rock and compacted gravel surfaces.
- Typical conditions for road-building, construction, and open-pit mining.
- Most tires wear out normally but some fail due to non-repairable punctures, for example, rock cuts.

High applications:

- Continuous use on short poorly maintained haul routes.
- High rolling resistance and poor traction surfaces.
- High impact loads to the tyres are likely.
- Almost all tires fail prematurely due to rock cuts, impacts, and non-repairable punctures, etc.

Initially, a detailed cost analysis was performed to determine the owning and operating costs for each vehicle during low, medium, and high applications. The cost analysis was based on a five-year ownership period with an estimated usage of 2000 hours per year.

Next, a productivity analysis was performed using the whole-body vibration data gathered from the validated computer models of the vehicle. Three notional but representative tasks were created for each application, namely, low, medium, and high. This type of analysis is performed routinely in plant management and is called off-the-job production planning [7]. Each task consisted of estimating the time to load a vehicle with a full payload, perform a haul journey to the destination, shed the payload, and return unladen to the original loading point. The productivity is calculated by dividing the payload delivered by the time taken to complete the circuit. The following routes were devised.

Low application:

- 3km level haul road with unprepared top surface with
  - Continuous 25mm RMS surface
- 6km round trip

Medium application:

- 1.5km level haul route with
  - 750m section of 25mm RMS surface
  - 500m section of 50mm RMS surface
  - 250m section of 75mm RMS surface
- 3km round trip

High application:

- 850m level quarry floor with
  - 250m section of 50mm RMS surface
  - 600m section of 75mm RMS surface
- 1.7km round trip

The speed attainable on any section of haul road was determined using interpolation of the results gained from the computer models. The maximum speed for any condition, laden or unladen, is determined on each road surface as the speed that provides a ride index of 0.8 m/s^2. This level of ride index was chosen based on a scale provided in [3]. A ride index of 0.8 m/s^2 is described as just beginning to feel 'uncomfortable'. It was assumed that an operator could withstand vibration up to this level whilst maintaining maximum productivity.

Once the hourly cost and productivity are known, equation 1 may be used to calculate the machine performance metric. Using the ride index criterion set out here, it is then possible to establish the time required to reach the action level and limit level of vibration dose.

4 RESULTS

Table 1 shows the results from the comparative study described in section 3.2. Hourly cost (combined owning and operating costs), productivity, and performance metric (M) are quoted for each vehicle and each application.

Table 1. Results from the Productivity Study

	Solid Axle Suspension	*Independent Suspension*
Low Application		
Hourly Cost(€/hour)	72.60	73.23
Productivity(ton/hour)	123	179
Performance,M(€/ton)	0.59	0.41
Medium Application		
Hourly Cost(€/hour)	76.19	76.87
Productivity(ton/hour)	101	156
Performance,M(€/ton)	0.75	0.49
High Application		
Hourly Cost(€/hour)	84.56	85.32
Productivity(ton/hour)	90	131
Performance,M(€/ton)	0.94	0.65

In addition to the productivity analysis, a health analysis was also performed, which was carried out in accordance with the vibration dose levels quoted in [4]. For the health analysis, the scenario was changed so that each vehicle would perform the tasks at the same speed. Hence, the vehicle with solid axle was asked to perform at the same productivity rate as the independent suspension vehicle. Using this scenario, we could compare the impact on health for each vehicle performing identical jobs.

Table 2. Results from the Health Study

	Solid Axle Suspension	*Independent Suspension*
Low Application		
Exposure time to limit level (hours)	3	50
Number of haul cycles to reach limit	22.9	357.5
Medium Application		
Exposure time to limit level (hours)	4	22.9
Number of haul cycles to reach limit	19	116.2
High Application		
Exposure time to limit level (hours)	10	50.1
Number of haul cycles to reach limit	13	64.8

5 CONCLUSIONS

It was demonstrated, using valid computer modelling techniques, that an articulating dumper vehicle fitted with a Timoney Independent suspension system is approximately 50% more productive for a variety of application scenarios than the same vehicle fitted with a solid axle suspension system. In addition, when both vehicles are asked to perform at the same productivity level, the vehicle with Timoney independent suspension can perform for longer than an eight-hour working period before reaching the limit level. In contrast, the vehicle with solid axle typically exceeds the limit before eight hours, increasing the health risks.

REFERENCES

[1] M.J. Griffin, *Handbook of human vibration*, Academic Press, First edition, 1996.

[2] N.J. Mansfield, *Human Response to Vibration*, CRC Press, First edition, 2004

[3] International Organization for Standardization, *Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – part 1: General Requirements*, ISO 2631-1:1997(E), Second edition, 1997

[4] *Directive 2002/44/EC*, Official Journal of the European Communities, L177/13, 2002

[5] International Organization for Standardization, *Mechanical vibration – Road surface profiles – Reporting of measured data*, ISO 8608:1995(E), First edition, 1995

[6] T.D. Gillespie, *Fundamentals of Vehicle Dynamics*, SAE International, 1992

[7] W. Moore, Field Test, *Construction Equipment*, March, 2001