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Effects of central tire inflation systems on ride quality of agricultural vehicles

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Abstract

Instrumentation to collect ISO2631 ride data was installed on a CaseIH 8950 tractor equipped with a central tire inflation system (CTIS). Data were collected at two speeds on three courses representing degraded secondary roads, moderately rough fields, and the toughest of farming conditions. Reductions in tire pressures available with central tire inflation resulted in greater tire deflections and, consequently, a smoother ride. The CTIS improved the ride of the vehicle by 99% over properly inflated tires on average, and by 177% when not in resonance.

Keywords: CTIS; ISO2631; Ride; Comfort; Tractor; Central tire inflation

1. Introduction

Any operator of agricultural vehicles knows that the ride can be particularly rough in a field due to the harmonic excitation caused by the spacing of the rows.

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Most research and solutions to improving the ride of agricultural vehicles to date have focused on suspending either the cab of the vehicle or the operator seat. If the operator has ever reduced the inflation pressure in radial tires, they know that the ride can be greatly improved by reducing the inflation pressure. Since the tires are the only primary suspension on most agricultural vehicles, a central tire inflation system (CTIS) would seem to be a reasonable choice of technologies to improve the ride of the vehicle without a substantial redesign or increase in cost.

Since the benefits of CTIS were demonstrated in World War II, CTIS has become standard equipment on most wheeled military vehicles [1]. CTIS allows the tires to dynamically change to lower inflation pressures to accommodate speed in rough terrain. The reduced pressure allows the tire to be more compliant, thereby maintaining better ground contact, as well as giving the operator a more comfortable ride. The military demonstrated that use of CTIS leads to improved traction, ride, and mobility for tactical vehicles, particularly in off-highway conditions [1].

In agriculture, CTIS has been a subject of discussion for some time [2]. However, other than the adaptation of the Mercedes Unimog and an aftermarket system manufactured in Germany, the major Original Equipment Manufacturers (OEMs) of agricultural equipment have not produced any commercial applications of CTIS. Although there are no OEM products on the market at this time, Case Corporation had two patents granted [3,4] related to CTIS for agricultural vehicles, and Deere and Company had one patent granted [5].

Some of the enabling factors for central tire inflation were advances in tire technology. Although radial ply tires were first developed for tractors in the late 1950s, they were not widely used in agriculture until the 1980s. Early research using radial tires consistently showed an increase in tractive performance [6]. In the early 1990s, the Tire and Rim Association (Copley, OH) adopted a new load inflation table, with minimum inflation pressures reduced to 40 kPa. As the inflation pressure was reduced, the footprint of the tire became larger and distributed the load over a larger area, helping to reduce the motion resistance in soft soils. Not only did the reduced inflation pressure decrease compaction, it also enhanced traction in soft soils since the area of soil providing the traction became larger, and more lugs were in contact with the soil. Also, as the inflation pressure was reduced, the stiffness of the tires was reduced. The softer tires maintained better ride quality by flexing to accommodate for unevenness in the terrain. The 50% reduction in minimum inflation pressure given by the new inflation tables for radial ply agricultural tires increased the vehicle performance when using CTIS, making the economic aspects of central tire inflation even more appealing.

1.1. Operator comfort

Kaczmarek [1] reviewed the history of CTIS and described several applications on military vehicles. He stated that in addition to the mobility improvement from the lower ground pressure and from better traction, CTIS also improved the ride and handling of tactical vehicles due to the increased compliance of the tires in rough terrain. The reduction in energy absorbed by the operator and vehicle components caused a decrease in fatigue and component failure rates.

Agricultural vehicles were at the top of the list for vehicles that transmit high levels of acceleration to the operator [7]. As the operating speed of agricultural vehicles increased, ride became a growing concern. Not only did poor ride and vehicle handling contribute to operator discomfort, fatigue, and poor performance; it also contributed to vehicle instability, including loss of control and rollover.

Two ISO Standards were preferred in evaluating the ride of agricultural vehicles. The ISO2631 [8–10] standard was a general standard for evaluating whole body vibration levels. In agriculture, the ISO5008 [11] standard was developed to measure the whole body vibration of the operator. The ISO5008 standard provided methods and procedures for measuring the ride characteristics of agricultural vehicles.

Since vibration can affect the comfort, efficiency, alertness, and health of a human operator, the ISO2631/1 [8] standard was developed to evaluate the severity of exposure of the human body to vibration. The standard was based on existing data and limits for vibration exposure, mostly from pilots and drivers. The standard was particularly oriented toward vibration transmitted through a surface to a person who was standing or sitting. The standard provided exposure limits in three different categories:

Exposure limit. The exposure limit was considered to be the maximum allowable limit for human safety. Exceeding the exposure limit was never recommended, even when no task was being carried out. The exposure limit was set at $\approx$1/2 of the acceleration levels that were considered painful.

Fatigue-decreased proficiency boundary. The fatigue-decreased proficiency boundary was considered to be the point where there existed a significant risk of impairing the ability of the operator to perform required tasks associated with operating the vehicle. The fatigue-decreased proficiency boundary was found to be 1/2 of the acceleration levels of the maximum exposure limits.

Reduced comfort boundary. The reduced comfort boundary was considered mainly in passenger vehicles for comfort considerations. The reduced comfort boundary was considered to be the point where carrying out tasks such as eating, drinking, reading, and writing became difficult. The reduced comfort boundary was found to be 1/3 of the acceleration levels of the fatigue-decreased proficiency boundary.

The human vibration exposure limits were sensitive to the frequency of vibration. At higher frequencies, the tissues of the human bodies acted as suspension systems that effectively isolate the body and organs from the vibration. Between 4 and 8 Hz the organs of the body tended to resonate, thus causing the most harmful effects. As the frequency of the vibration decreased, effects were somewhat reduced in the vertical direction. As the frequency decreased below 1 Hz, people tended to get motion sickness. For this reason, a minimal amount of data was taken at frequencies below 1 Hz, limiting the scope of the standard to frequencies between 1 and 80 Hz.

The goal of this research was to evaluate the effect of CTIS on the ride of an agricultural vehicle. A CaseIH 8950 tractor was equipped with a CTIS, and instrumentation to measure accelerations in the lateral, longitudinal, and vertical directions at the seat base. Data were collected to determine fatigue-reduced proficiency boundary across courses representative of an agricultural environment.

2. Methods

Ride quality of the tractor was evaluated at the Nevada Automotive Test Center (NATC) in Silver Springs, Nevada. Three course profiles were used to evaluate the ride of the vehicle:

Belgium block. A representative course of a degraded secondary road in Belgium.

Medium farm field roughness. A course that represented profile data taken from a series of moderately rough fields selected to represent a wide range of vehicle operating conditions.

High farm field roughness. The profile represented the toughest of farming conditions including bedded crops, ripped soil, and other extreme conditions.

All courses were hard surfaced with either concrete or asphalt. Each of the farm field roughness courses consisted of two lanes. The lanes could either be straddled or run individually if the vehicle was not too wide (no duals). The farm field roughness courses were constructed based on elevation profiles from a composite of several different types of cropping conditions, including row crops and bedded crops. The Belgium Block course was selected, in addition to the farm field roughness courses, because it approximated many poorly maintained farm roads with high roll inputs to the vehicle.

Inflation pressures representing a central tire inflation condition (P1), a properly inflated condition (P2), and a typical over inflated condition (P3) were included in the experiment. The inflation pressures for each tire at each of the three inflation conditions are shown as P1, P2, and P3 in Table 1. High and low operating speeds were selected for each course. The high speed was set to 75% of the maximum speed that the operator felt that they could safely operate the vehicle when the tires were inflated to the proper tire inflation pressure. The low speed was set to 75% of the high speed. The low and high speeds for each course are as follows: high farm field roughness courses – 12 and 16 km/h, medium farm field roughness courses – 19 and 26 km/h, and Belgium block – 19 and 26 km/h. When the single tires were used, in addition to the straddle of the farm field courses, seat acceleration data were collected for operation on both lanes individually for the medium and high farm field roughness courses. Only a 35/65 front-to-rear weight split or lower could be used while maintaining a constant total vehicle weight of 102 kN when the duals were added and removed. The test matrices were replicated three times for a total of 180 runs. The experiments were run in two blocks consisting of single and dual rear tires.

Since the test courses were hard surfaced and the data acquisition was in a controlled environment, test course degradation and temperature drift had no noticeable

Table 1
Inflation pressures used in CTIS experiments

Tire inflation pressure level (kPa)	Singles		Duals	
	Front	Rear	Front	Rear
CTIS (P1)	62	69	62	21
Proper (P2)	83	103	83	41
Overinflated (P3)	103	138	103	62

effects on the experiment. The small value for the sum of squares error in the analysis of variance indicated the repeatability of the data was good.

The data were analyzed using custom scripts written for Matlab 5.2 (The MathWorks, Inc., Natick, MA). The scripts calculated a Power Spectral Density (PSD) curve for the acceleration data at the base of the seat. The data from the seat were not used, since the resonance of the seat suspension caused amplification of the acceleration. The fatigue reduced proficiency boundary limits from the ISO2631/1 standard were used to determine the allowable daily operator exposure to the vibration from operating the tractor.

Although the ISO2631/1 standard provided an equation to combine the acceleration data to calculate the allowable daily exposure, past experience indicated that the individual consideration of each axis presented results that more closely agreed with the opinion of the operators. Each axis was considered individually, and the minimum fatigue-reduced proficiency boundary (in hours) of the three axes was used as the overall limit for vehicle evaluation. The vertical axis tended to produce the lowest allowable daily exposure.

3. Results and discussion

The ISO2631 standard was used to compute the fatigue-reduced proficiency boundary for each set of data. The results were averaged for each course, inflation pressure, tire configuration, and speed. The results showed improvement in ride with reductions in tire pressure, and additions of duals.

The average allowable exposures for each set of courses (medium roughness, MR; high roughness, HR; and Belgium blocks, BB) were found to be 8.3, 8.6, and 9.4 h, respectively. The initial values for the high speed setting for each set of courses were set at a value of 75% of the maximum speed that an operator could control the vehicle. For this reason, when the allowable exposure for the courses were examined in Fig. 1, variance in the average allowable exposure was seen due to the physical differences in the construction of the course. The 25% decrease from the high to low speed resulted in a 30% improvement in allowable exposure as seen in Fig. 2.

Video of the operation of the tractor showed that the wheels occasionally left the ground in the rougher locations on the courses. When the tires lose contact with the ground, no damping can occur from the deflection of the tire, thereby increasing the duration of the vibration of the vehicle. To achieve good ride quality, the tires must maintain contact with the ground to dissipate the unwanted energy from the oscillation of the vehicle. To accomplish this, the deflection or travel in each tire could be increased. The resonant frequency (f) of a mass–spring system is:

$$\left(f = \frac{1}{2\pi}\sqrt{\frac{K}{m}}\right).$$

If the stiffness (K) of the suspension is written in terms of mass (m), gravity (g), and deflection (δ):

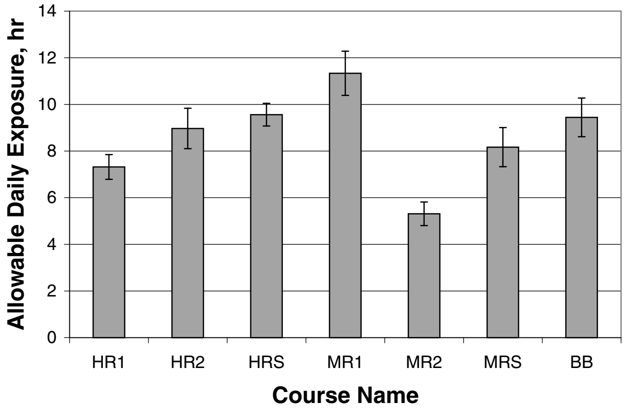

Fig. 1. Average ISO2631 average allowable daily exposure for each course. A higher allowable exposure was better. Error bars represent one standard deviation of the allowable exposure. Course key: HRx = high farm field roughness, MRx = medium farm field roughness, BB = Belgium block, xx1 = north lane, xx2 = south lane, xxS = straddle north and south lane.

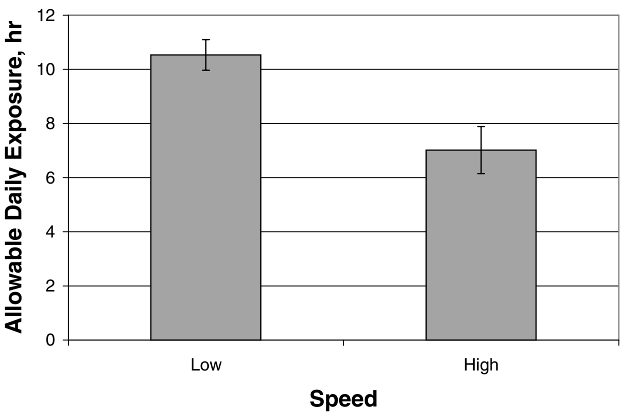

Fig. 2. Average ISO2631 allowable daily exposure for low and high speeds. A higher allowable exposure was better. Error bars represent one standard deviation of the allowable exposure. Low speed was 19 km/h for the medium farm field roughness courses and the Belgium block course and 12 km/h for the high farm field roughness courses. High speed was 26 km/h for the medium farm field roughness courses and Belgium block course, and 16 km/h for the high farm field roughness courses.

$$\left(K = \frac{mg}{\delta}\right).$$

The stiffness in terms of deflection can be substituted into the resonant frequency equation to determine the resonant frequency of the system based on the deflection:

$$\left(f = \frac{1}{2\pi}\sqrt{\frac{g}{\delta}}\right).$$

A deflection of 25 cm would give the vehicle a resonant frequency of 1.0 Hz. A deflection of 10 cm would achieve a ride quality suitable for most agricultural vehicles as operated today by allowing a resonant frequency of 1.6 Hz for the vehicle.

As the air was released from the tires, the deflection increased if the load remained constant. Central tire inflation allowed the air pressure to be reduced as the speed slowed, thereby increasing the deflection and improving the ride as the vehicle was operated at a speed less than the road transport speed. For the rear tires, the decrease in inflation pressure resulted in an increase in static deflection from 16.8% to 25.4% (7.3–11.1 cm). The corresponding measured resonant frequency dropped from 1.85 to 1.50 Hz, identical to the values calculated from the static tire deflection. Fig. 3 shows the improvement in allowable daily exposure as the pressure was decreased from the over inflated condition to the properly inflated condition to the central tire inflation condition. It should be noted that the deflection of the tire was related to the inflation pressure by an exponential function. The exponential relationship of the ride to the tire pressure would indicate that once a significant improvement could be seen from adjusting the tire inflation pressure, any additional reduction in tire pressure would cause an even more substantial improvement in ride quality, provided that the tire does not overheat.

When dual tires were added to the vehicle, Fig. 4 shows a 10% improvement in allowable daily exposure. The most likely reason the duals improved the ride was that the roll stiffness of the vehicle was improved. Although the data showed the limiting factor was vertical vibration in most cases, lateral vibration caused by the roll of the vehicle was the limiting factor 5% of the time.

An analysis of variance (ANOVA) was also conducted on the ISO2631 fatigue-reduced proficiency boundary computed from the ride data for the single and dual rear tire experiments. The ANOVA showed the sum of squares for the error term in both cases was small. The small level of error caused all factors (Speed, Course, and Pressure) to be significant at the $\alpha = 0.01$ level for the F-test. The Pressure, Speed,

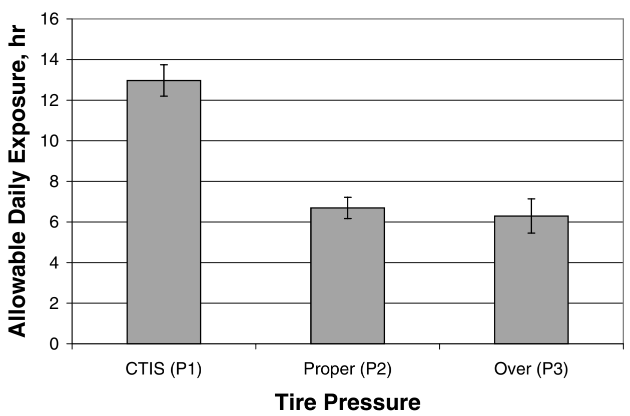

Fig. 3. Average ISO2631 allowable daily exposure versus inflation pressure. A higher allowable exposure was better. Error bars represent one standard deviation of the allowable exposure.

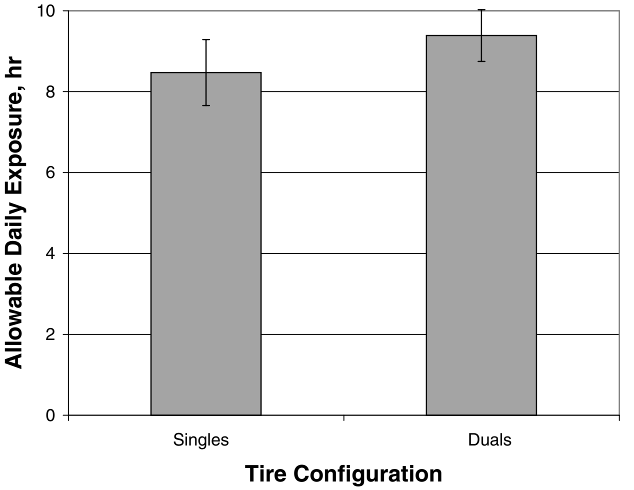

Fig. 4. Average ISO2631 allowable daily exposure for single and dual tires. A higher allowable exposure was better. Error bars represent one standard deviation of the allowable exposure.

and Pressure × Speed interaction were more significant than any other factor or interaction by an order of magnitude.

The physical explanation for the strong significance of the interaction related to the spectral density of the courses and the fact that the courses included specific harmonics to represent operation perpendicular to bedded and row crops. As the speed changed, the forcing frequency from the courses changed. As the pressure changed, the resonant frequency of the vehicle changed. At the CTIS pressure, high-speed combination, the forcing frequency and the resonant frequency of the vehicle were nearly the same, reducing the improvement in performance at the CTIS pressure, high-speed combination for all courses.

When going from proper tire pressure to CTIS tire pressure, the actual ride improvement varied from 18% to 222% improvement. An average of 177% improvement in ride was seen at the low speed settings where the vehicle was not resonating due to the harmonics of the test course. When the harmonics of the test course were forcing vibration of the vehicle at the natural frequency for the CTIS pressure, high-speed combination, the ride was only improved 21% on average. The average improvement in ride for all test trials and conditions when decreasing from the proper tire pressure to the CTIS pressures was 99%.

4. Conclusions

Reductions in tire pressures resulted in greater tire deflections and, consequently, nearly always produced a smoother ride. The reduction in inflation pressure caused a reduction in the resonant frequency of the vehicle from 1.85 to 1.5 Hz. Reductions in tire inflation pressure due to the installation of a CTIS improved the ride of the vehicle by 99% on average when evaluated with the ISO2631 standard. Reductions in tire inflation pressure due to the installation of a CTIS improved the ride of the vehicle by 177% when not in resonance. The addition of dual rear tires improved the ride of the vehicle by 10%.

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References

[1] Kaczmarek RW. Central tire inflation systems (CTIS) – A means to enhance vehicle mobility. In: Proceedings of the Eighth International Conference of the ISTVS. England: Cambridge; 1984.
[2] Hassan AE. A prime mover equipped with central tire inflation system. ASAE Paper No. 83-1055. St. Joseph, MI: ASAE; 1983.
[3] Schmitz GW. Seal arrangement for a central tire inflation system. US Patent No. 6,145,558. US Patent and Trademark Office; 2000.
[4] Adams BT, Schmitz GW. Automatic central tire inflation system. US Patent No. 6,144,295. US Patent and Trademark Office; 2000.
[5] Kis J. Tire pressure control system. US Patent No. 6,098,682. US Patent and Trademark Office; 2000.
[6] Forrest PJ, Reed IF, Constantakis GV. Tractive characteristics of radial-ply tires. Trans ASAE 1962;43(11):108, 115.
[7] Horton DNL, Crolla DA. Designing off-road vehicles with good ride behavior. In: Proceedings of the Eighth International Conference of the ISTVS. England: Cambridge; 1984.
[8] Anon. Evaluation of human exposure to whole-body vibration – Part 1: General requirements (ISO2631-1). International Organization for Standardization; 1985.
[9] Anon. Evaluation of human exposure to whole-body vibration – Part 2: Continuous and shock-induced vibrations in buildings (1–80 Hz) (ISO2631-2). International Organization for Standardization; 1989.
[10] Anon. Evaluation of human exposure to whole-body vibration – Part 3: Evaluation of exposure to whole-body z-axis vertical vibration in the frequency range 0.1–0.63 Hz (ISO2631-3). International Organization for Standardization; 1985.
[11] Anonymous. Agricultural wheeled tractors and field machinery – Measurement of whole-body vibration of the operator (ISO5008). International Organization for Standardization; 1979.