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AN INVESTIGATION REGARDING THE EFFECTS OF ACCELERATION PRODUCED BY CABIN SUSPENSION SYSTEMS FITTED TO AGRICULTURAL TRACTORS UPON THE OPERATOR, IN TERMS OF OPERATOR HEALTH

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Abstract

Operators of agricultural tractors are exposed to high levels of acceleration. This paper critically examines acceleration data (in the x and y axis) collected through practical tests. Data collected shows that when cabin suspension is fitted to agricultural tractors, operators are exposed to increased levels of acceleration, up to 62% and 25% at 2.5 kph in the x and y axis respectively, when compared to the respective chassis system. Acceleration above 5.98 m/s^2 may result in the operator developing musculoskeletal disorders (MSD). This limit is exceeded in the y axis at 17 kph by a four-point active cabin suspension. Moreover, the mass of the head/torso, will multiply acceleration measured at the seat base, by 2.5, therefore, this limit is exceeded at 6.5 kph in the y axis. Consequently, up to 62% of agricultural tasks have the potential for the operator to sustain MSD. Concerns have been raised regarding the current operational speeds of agricultural tractors; this is due to the potential for acceleration above 5.98 m/s^2, to be generated and transferred to the operator and can result in MSD.

Key words: *acceleration, tractors, cabin suspension.*

INTRODUCTION

Agricultural machinery operates within harsh terrain conditions which can result in high operator exposure to mechanical shocks (acceleration of the human anatomy) (Milosavljevic et al., 2011; Waters et al., 2007; Eager et al., 2016). Moreover, certain types of agricultural machinery (tractors, material handlers) are designed to be multipurpose vehicles, thus compatible with a range of implements/attachments (Caffaro et al., 2016). Furthermore, Langer et al. (2015), adds that the equipment the agricultural tractor is operating can induce mechanical shocks, e.g. a hay/straw baler. Although, Tiemessen et al. (2007) states that an agricultural tractor towing a loaded trailer may reduce mechanical shocks being induced upon the operator. Consequently, health conditions, such as musculoskeletal disorders (MSD), can be developed, although, mechanical shocks are not solely responsible for the development of MSD, other contributing factors include; whole body vibration (WBV), repetition, awkward working position, all the contributing factors can be classified as external motions (Eager et al., 2016; Mayton et al., 2008; Kim et al., 2018; Bovenzi & Betta, 1994).

Rehn et al. (2005; 2009), states that operators of mobile equipment report the development of MSD, in the neck and shoulder region of the human anatomy, as a result of exposure to external motions.

Furthermore, Caffaro et al. (2016) and Eager et al. (2016), state that external motions can damage the spinal structure, and joints of the human anatomy.

Concerns regarding the current operational speed of agricultural machinery have been raised by three authors; Melzi et al. (2014), Achen et al. (2008), Rehn et al. (2005), who suggest that the increased travel speed has the potential to reduce operator comfort and increase exposure to external motions, leading to the development of health conditions. Furthermore, Scarlett et al. (2007), states that WBV increases in correlation with the travel speed of the vehicle.

There are four areas on most agricultural machinery where suspension can be fitted, these consist of the; operator cabin, operator seat, axles, and the tyres (Figure 1) (Melzi et al., 2014).

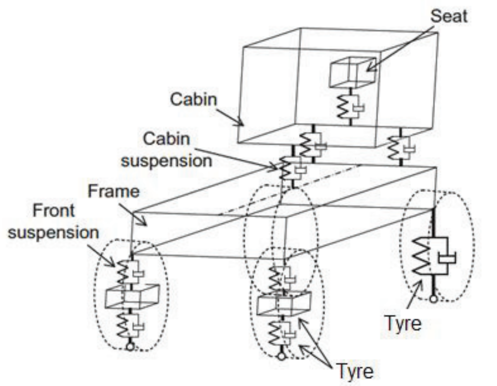

Figure 1. Diagram showing areas suspension can be fitted to agricultural vehicles (Melzi et al., 2014)

Cuong et al. (2013) and Melzi et al. (2014) state that agricultural tractor and machinery manufacturers, do not fit advanced cabin suspension systems to the operator cabin as standard equipment. Instead rubber based anti-vibration mounts are used (Lyashenko et al., 2016). This is despite Hansson (1995) suggesting that suspending the whole operator cabin can reduce mechanical shock transferred to the operator, additionally, Sim et al. (2017) added that operator weight does not detrimentally affect the performance of this type of suspension system. Operator weight is a limiting factor to seat suspension therefore, this can reduce the performance/effectiveness of seat suspension (Sim et al., 2017). According to Cuong et al. (2013), axle suspension can reduce the mechanical shocks experienced by the vehicle being transferred to the operator. Although Achen et al. (2008) states that this type of suspension system can further increase the cost of the vehicle, due to requiring to redesign structural components. Depending on the operating pressure of the tyres, a small amount of mechanical shock can be absorbed by the tyres (Tiemessen et al., 2007). Although, reducing the tyre inflation pressure, to reduce mechanical shocks, in turn increases the heat generated by the tyres and the rolling resistance of the tyres (Donati, 2002).

This paper will evaluate acceleration produced in the *x* and *y* axis (Figure 2), for three variants of cabin suspension. According to Kim et al. (2018), these two axes are not required to be suspended to comply with ISO 2631.

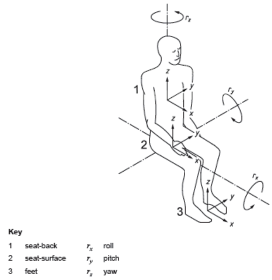

Figure 2. Diagram showing the *x*, *y*, *z* Axis Orientation, (ISO, 1997)

MATERIALS AND METHODS

Four individual elements were used to collected information and data to fully evaluate acceleration produced in the *x* and *y* axis. These four elements consisted of; investigating academic literature, conducting surveys which focused on agricultural workers, conducting interviews with agricultural manufacturers and finally completing practical tests.

The academic literature has been investigated to provide an understanding regarding the current suspension systems used on agricultural tractors and machinery. Additionally, academic literature provided an insight into the health implications for the operator as a result of long-term exposure to mechanical shocks and acceleration.

Surveys were conducted with agricultural workers and agricultural tractor and machinery operators. The surveys were distributed across the North West of the United Kingdom between December 2017 and February 2018 and focused on collecting both qualitative and quantitative data surrounding agricultural tractor operation. Additionally, the surveys collected data about the suspension systems fitted to their (the survey respondents) agricultural tractors, the final question in the survey asked if the respondent had awareness of long-term health effects as a result of exposure to mechanical shock and acceleration.

The interviews with eight agricultural manufacturers were conducted at LAMMA (Lincolnshire Agricultural Machinery Manufacturers Association) on the 17th January 2018, the interviews collected information regarding the current level of cabin suspension systems, which agricultural manufactures install to their agricultural tractors.

Practical tests on three types of cabin suspension systems were completed between November 2017 and February 2018. The practical tests were designed to determine the acceleration in both the *x* and *y* axis. The data has been collected using a data logger, which recorded acceleration (displayed as m/s^2), measuring at 100 Hz. Three types of cabin suspension systems were tested (mechanical, four and three point active). Semi active cabin suspension is another suspension system outlined by Van Iersel (2010), although none were available to test. The three cabin suspension systems were produced by the same agricultural manufacturer, although due to available resources, the current working hours of the agricultural tractors differed when the tests commenced. Additionally, the tyre condition, chassis size and machine age differed between the three agricultural tractors which were tested. The agricultural tractors which were tested all had the same front axle design (suspended beam axle), and the tyre pressures were set to the manufacture's recommendations.

The practical tests involved driving each agricultural tractor over a wooden obstacle which measured 1032 x 280 x 140 mm (length x width x height), at two test speeds, 2.5 and 5 kph. There were three configurations of the wooden obstacle (at each forward speed) allowing the left, right hand and both wheels to negotiate the wooden obstacle; this is shown below in Figure 3 as 1, 2, 3, respectively.

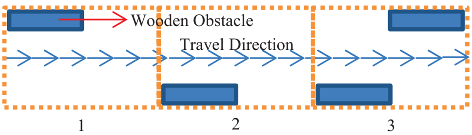

Figure 3. The three test track configurations

The test track varied in length between 11 and 13 metres depending on the forward travel speed 2.5 or 5 kph, respectively. The obstacles shown in Figure 3 above were positioned 4 meters into the course; this allowed the agricultural tractors to reach the desired speed of 2.5 or 5 kph prior to reaching the obstacle. All three agricultural tractors were fitted with a CVT gearbox and cruise control; this allowed consistent travel speeds to be selected.

To provide a comparison between the acceleration produced by the cabin and the chassis, two mounting points for the data logger were selected which could be replicated on all three agricultural tractors, these are shown below in (Figure 4 and 5).

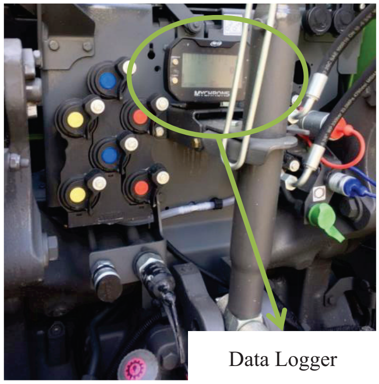

Figure 4. Data Logger Location (Chassis)

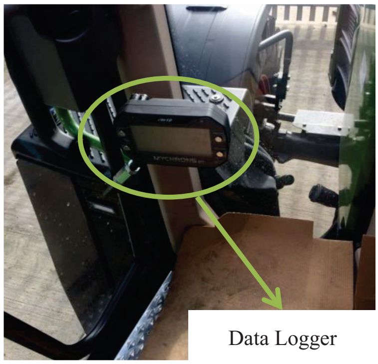

Figure 5. Data Logger Location (Cabin)

The practical tests were repeated 5 times, to provide accurate data collection, and allowing a mean to be calculated. On completion of the data collection Microsoft Excel has been used to post process the data. Post processing of the data determined the mean peak acceleration, for each wavelength on the acceleration traces of each test track configuration (Figure 3), completed at each travel speed. Once the mean peak acceleration had been calculated, for each test track configuration, the mean peak acceleration for the tests completed at the two travel speeds were combined to be provide a mean acceleration at a specific travel speed (2.5 and 5 kph) for each cabin suspension system tested. This data provided the bases to calculate an estimation of acceleration produced at travel speeds higher than 5 kph.

RESULTS AND DISCUSSIONS

Sorainen et al. (1998), states that mechanical shocks (acceleration) are unavoidable when operating machinery on uneven terrains, therefore, the correct equipment to protect the operator should be utilised. Hansson (1995) suggests cabin suspension should be fitted to agricultural tractors, reducing the operator exposure to acceleration.

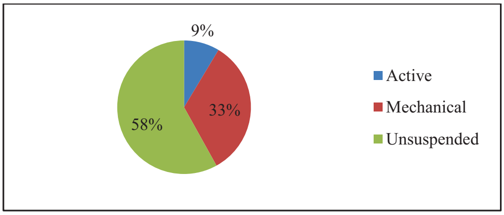

Figure 6. Chart showing the cabin suspension system fitted to the agricultural tractors surveyed

As shown in Figure 6, 58.0% of the cabins fitted to the agricultural tractors surveyed were unsuspended. This is despite one of the manufacturers interviewed commenting that customers expect cabin suspension systems to be offered as standard on large agricultural tractors. Although, as shown in Figure 7, the mean age of the agricultural tractors fitted with an unsuspended cabin is 19.56 years. Additionally, as show in Figure 7, the mean age of the agricultural tractors with fully suspended axles, is higher than the mean age of the agricultural tractors fitted with active cabin suspension, this could be explained due to only 4.0% of the agricultural tractors surveyed being fitted with fully suspended axles. Moreover, as shown in Figure 8, the mean yearly operational hours for the unsuspended cabins is 432, as expected Figure 8 shows that the yearly operational hours positively correlate to the increased level of suspension system installed to the vehicle. Furthermore, Figure 10, shows that unsuspended cabins are used in rough terrain conditions (yards and fields) for the highest yearly percentages, 21.46% and 14.94%, respectively, when compared against the other suspension systems which were considered in this report. Therefore, there is a potential for increased operator exposer to acceleration in these terrain conditions.

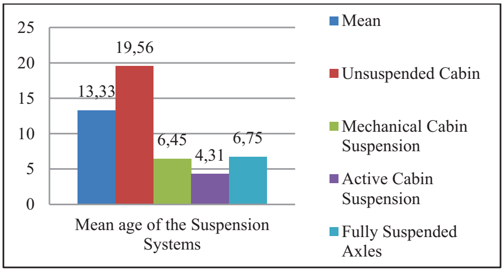

Figure 7. Chart showing the mean age of the agricultural tractors surveyed, categorised by suspension systems

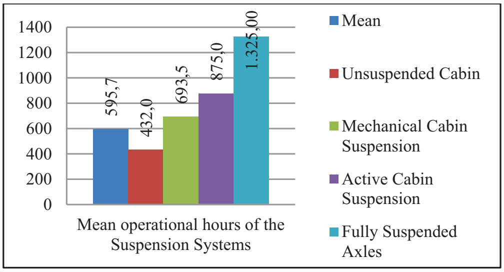

Figure 8. Chart showing the mean operational hours of the agricultural tractors surveyed, categorised by suspension systems

According to Johanning (2015), there is a correlation between increased spinal disorders and increased intensity/ duration of exposure to mechanical shocks. Milosavljevic et al. (2010), adds this is due to increased spinal loading in the lumbar vertebrae of the spinal structure, (Figure 9). This increased loading is through the intervertebral end plates (the top and bottom of each vertebral body), and the lumbar intervertebral discs, this is shown below in Figure 11.

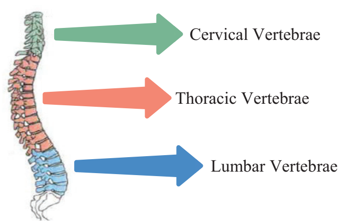

Figure 9. The vertebral column (Marieb, 1998)

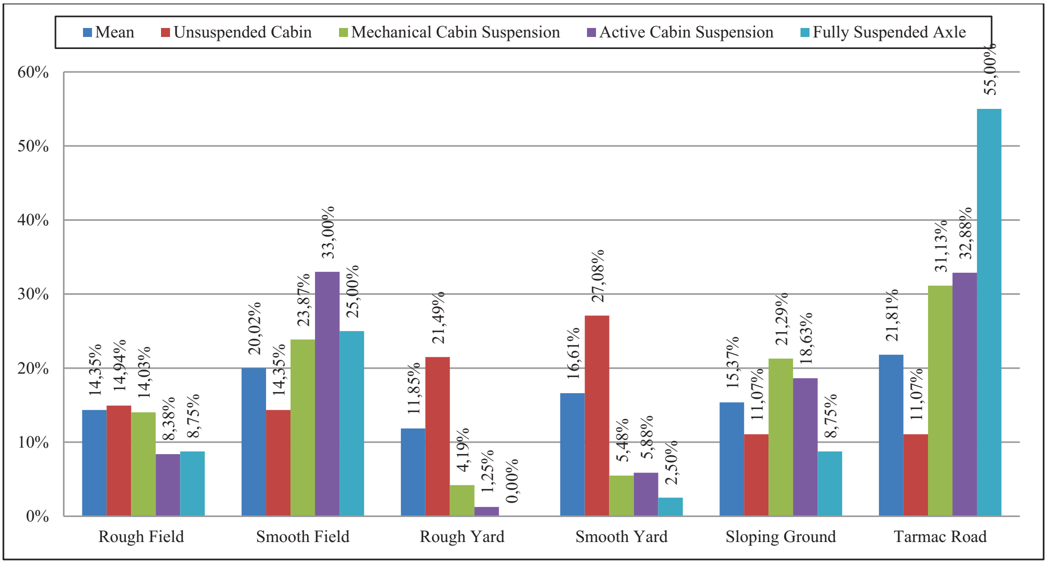

Figure 10. Chart showing the mean percentage of yearly operation in given terrains, for each suspension system respectively

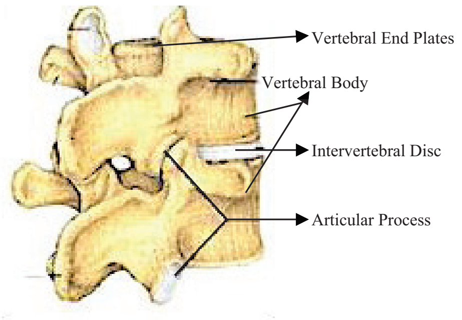

Figure 11. Annotation of the Lumber Vertebrae (Marieb, 1998)

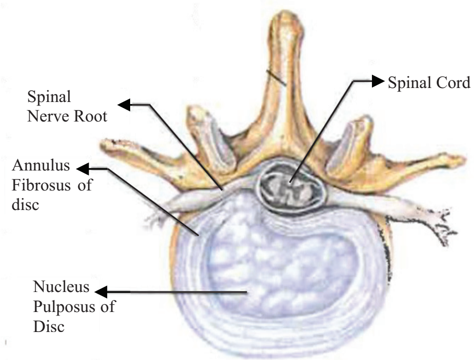

Figure 12. Annotation of the vertebrae (Marieb, 1998)

Waters et al. (2007) and Bovenzi (2006) state that the lumber region is the first area of the spinal structure which is susceptible to damage when exposed to mechanical shock. Additionally, Wikström et al. (1994) and Waters et al. (2008) state that when the spine is in a twisted position the spinal structure is at a higher risk of being damaged by mechanical shocks. Moreover, this is a common occurrence for operators of agricultural machinery, as they are required to frequently turn their head to inspect the rear of the machine (Wikström et al., 1994). Furthermore, Waters et al. (2007), states that vehicle induced mechanical shocks contributes to 36.0% of lower spinal injuries.

Waters et al. (2007) states that the vertebral end plates can deform/misalign under load (mechanical shock), this allows the hydrated nucleus pulposus (Figure 12) to herniate the endplate. This results in a pressure reduction of the nucleus pulposus, the decompressed disc bulges and loses height (degeneration of the intervertebral disc). Additionally, Bovenzi and Betta (1994), states that degeneration of the intervertebral discs is a contribution factor to lower back pain. Moreover, Kim et al. (2018) and Milosavljevic et al. (2010) add the balance and vision of the operator may be reduced as a result of degenerating intervertebral discs. Furthermore, Sorainen et al. (1998), states that intervertebral discs loose water throughout the day, and exposure to mechanical shocks accelerates the reduction of water in the intervertebral discs. When the intervertebral discs loose water they start to narrow, this reduces the function of the spine. Additionally, the nutrient pathways to the spinal articular processes are damaged with exposure to mechanical shock (Milosavljevic et al., 2010). The intervertebral discs are the largest none vascular part of the human anatomy which has no biological repair process, and therefore, should be protected from exposure to mechanical shock (Wikström et al., 1994). Moreover, operator exposure to acceleration can decrease operator productivity (Taghizadeh-Alisaraei, 2017).

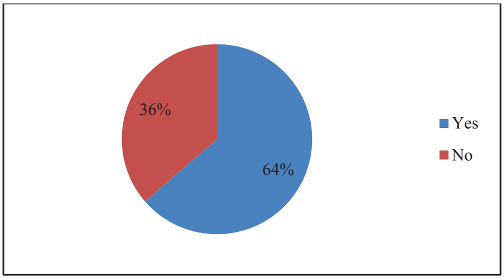

Figure 13. Chart showing the respondents awareness to health effects after exposure to mechanical shocks

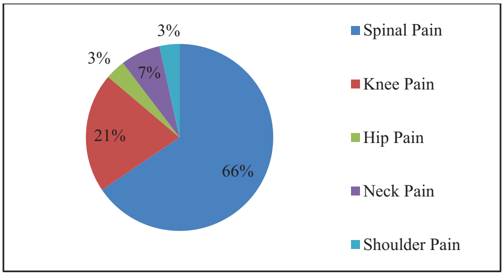

Figure 14. Chart showing areas of the human anatomy which respondents felt the prevalence of pain when exposed to mechanical shocks, whilst or shortly after operating agricultural machinery

As shown in Figure 13, 64.0% of respondents were aware of the potential to develop health issues as a result of exposure to mechanical shocks. Additionally, 66.0% of these respondents related exposure to mechanical shocks to developing spinal pain, as shown in Figure 14. Although, as shown in Figure 13 and described by Solecki (2012), there is a proportion of the respondents who are not aware of the health effects as a result of exposure to mechanical shocks.

According to Wikström et al. (1994), acceleration/mechanical shock above 5.98 m/s^2 (threshold limit) can cause damage to the intervertebral discs, additionally, mechanical shock/acceleration in the *x* and *y* axis are accelerated by the mass of the head/torso. Additionally, Kim et al. (2018) adds that acceleration measured at the head/torso is 2.5 times greater than acceleration measured at the base of the seat.

As shown in Table 1 below, in all but one test scenario the cabin produced higher levels of acceleration, than the acceleration measured at the chassis. Furthermore, the increased acceleration of the cabin is up to 62.0% and 25.0% higher than the chassis at 2.5 kph, in the *x* and *y* axis respectively, for the mechanical cabin suspension system tested. The difference between cabin and chassis acceleration (in the *x* axis) does reduce with the implementation of increased cabin suspension systems. Although, acceleration in the *y* axis does not display the same trend (with regards to reduction), seen for cabin/chassis acceleration in the *x* axis.

Table 1. Summary of the practical test data

		X Axis		Y Axis	
Cabin Suspension System	Travel Speed (kph)	2.5	5	2.5	5
Mechanical (Cabin Acceleration) (m/s^2)		0.745	0.981	0.824	1.530
Mechanical (Chassis Acceleration) (m/s^2)		0.461	0.686	0.657	1.402
Percentage Difference (Cabin/Chassis)		*62%*	*43%*	*25%*	*9%*
Four Point Active (Cabin Acceleration) (m/s^2)		0.637	0.912	0.951	1.814
Four Point Active (Chassis Acceleration) (m/s^2)		0.490	0.657	1.049	1.167
Percentage Difference (Cabin/Chassis)		*30%*	*39%*	*-9%*	*55%*
Three Point Active (Cabin Acceleration) (m/s^2)		0.588	0.775	0.598	1.451
Three Point Active (Chassis Acceleration) (m/s^2)		0.500	0.755	0.481	1.089
Percentage Difference (Cabin/Chassis)		*18%*	*3%*	*24%*	*33%*

Figure 17 and Figure 18 shows an estimated acceleration in the *x* and *y* axis for travel speeds from 2.5 to 40 kph, for the three tested cabin suspensions, in addition, an estimated acceleration produced by an unsuspended cabin is shown. The estimated acceleration produced by an unsuspended cabin is a combination of the estimated acceleration measured on all of the chassis tested.

As shown in Figure 17, acceleration at speeds above the maximum test speed (5 kph), is below the 5.98 m/s^2 threshold limit, for all the cabin suspension systems considered. Although when the acceleration data is multiplied by 2.5, to determine the acceleration of the head/torso, the 5.98 m/s^2 threshold limit, is exceeded at 20, 18.5, 27, 25 kph by the mechanical, four/three-point active cabin suspension system and an unsuspended cabin respectively (in the *x* axis). Furthermore, at 40 kph the three-point active suspension system reduces the acceleration in the *x* axis by 9.6%, when compared to the acceleration produced by an unsuspended cabin.

As shown in Figure 18, acceleration measured in the *y* axis is up to 50.0% greater than acceleration measured in the *x* axis, (at 2.5 kph). Additionally, the threshold limit of 5.98 m/s^2, is exceeded by all the cabin suspension systems considered in this report between 2.5 and 30 kph. Moreover, when the acceleration data is multiplied by 2.5, to determine the acceleration of the head/torso. The 5.98 m/s^2 threshold limit is exceeded between 2.5 and 11 kph. As shown in Figure 18 the unsuspended cabin produced the lowest levels of acceleration in the *y* axis, followed by the mechanical, three/four-point active cabin suspension system. Despite the mechanical cabin suspension system recording the second lowest acceleration trace in the *y* axis at 40kph, the acceleration trace is 29.0% higher than the acceleration produced by an unsuspended cabin. Moreover, the three/four-point active cabin suspension acceleration trace is 39.5% and 41.7% higher than the acceleration produced by an unsuspended cabin, at 40 kph.

As shown in Figure 15, between 52.0% and 62.0% of the given field operations completed with agricultural machinery using one of the three cabin suspension systems tested have a potential for the operator to cause damage to their intervertebral discs. Although, it is interesting to note due to the low speed of the field operations (maximum of 10 kph), the acceleration threshold of 5.98 m/s^2 is not exceeded by an unsuspended cabin, in the *y* axis. According to Taghizadeh-Alisaraei (2017), operator exposure to acceleration is greater in developing countries, due to agricultural tractors not utilising the latest technologies, and are being operated for long periods of time in rough terrain conditions.

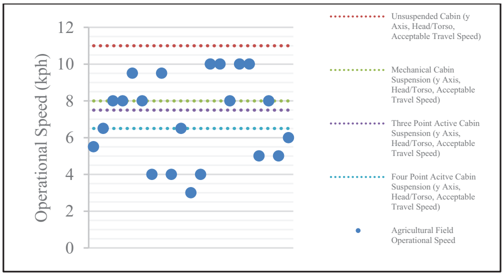

Figure 15. Chart showing the typical operational speeds for a range of field activities described by Landers (2000), additionally, the chart shows the acceptable travel speed (ensuring acceleration is not above 5.98 m/s^2 in the *y* axis (head/torso), preventing damage occurring to the operator's intervertebral discs) for all of the cabin suspension systems considered in this report

UK Legislation, amended in 2015, increases the travel speed of conventional agricultural tractors to 40 kph, from 32 kph without any design alterations (Collins, 2015). As shown in Table 2, increasing the travel speed by 8 kph, the estimated acceleration (in the *y* axis for the head/torso) is increased by up to 115.0% (32 to 40 kph). Additionally, at 40 kph the estimated acceleration, (in the *y* axis for the head/torso), is up to 481.0% above the 5.98 m/s^2 threshold limit described by Wikström et al. (1994).

As shown above in Figure 8, the surveyed agricultural tractors are operated between 432.0 and 1,325.0 hours per year, depending on the suspension system installed to the vehicle. Furthermore, Johanning (2015), Bovenzi (1996), and Kittusamy & Buchholz (2004), state that the period of exposure to acceleration, is a high contribution to operators sustaining lower back injuries. Moreover, as shown in Figure 16, the operational hours of agricultural tractors vary depending on the month. This is due to the agricultural activities which require an agricultural tractor peaking twice a year, (month 4 and 8), these activities include soil cultivation, harvesting and produce transport. Additionally, Solecki (2012), states that agricultural tractors may be operated for up to 16.3 hours during peak operational periods of the year.

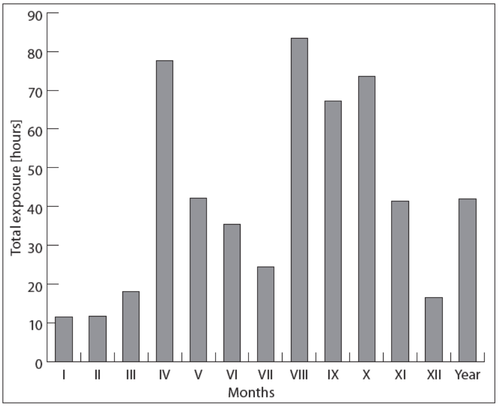

Figure 16. Monthly Operation Hours of agricultural tractors (Solecki, 2012)

Commercial vehicles which are used for hire or reward are subject to stringent daily and weekly operator hour regulations, additionally, regular breaks are required to be taken (EOS, 2017). Commercial vehicles and agricultural tractors used for purposes relating to; agriculture, horticulture, forestry, farming, or fishery, are exempt from the EU operator hour regulations, as-long-as the vehicle is operated within a 100km radius of the business site (Government Digital Service, 2015). Although, the operators are still subject to UK domestic driver hour regulations where a daily maximum of 10 hours applies, only time operating on public highways are counted towards the 10 hours daily limit (Government Digital Service, 2015). Moreover, operators are eligible to opt-out from the UK domestic driver hour regulations (EOS, 2017). Therefore, operators may be exposed to acceleration for extended periods of time.

Table 2. Table showing the % increase in estimated acceleration between 30 and 40 kph travel speed

		32 kph (m/s^2)	% above 5.98 m/s^2	40 kph (m/s^2)	% above 5.98 m/s^2	Percentage increase between acceleration above 5.98 m/s^2 at 32 kph and 40 kph
	x Axis					
Estimated Acceleration	Unsuspended	3.02	-49%	3.71	-38%	11%
	Mechanical	3.52	-41%	4.28	-29%	13%
	Four Point	3.87	-35%	4.76	-20%	15%
	Three Point	2.79	-53%	3.38	-43%	10%
	x Axis					
Estimated Head/Torso Acceleration	Unsuspended	7.55	26%	9.27	55%	29%
	Mechanical	8.81	47%	10.69	79%	31%
	Four Point	9.70	62%	11.90	99%	37%
	Three Point	6.96	16%	8.45	41%	25%
	y Axis					
Estimated Acceleration	Unsuspended	6.54	9%	8.11	36%	26%
	Mechanical	9.16	53%	11.41	91%	38%
	Four Point	11.13	86%	13.90	132%	46%
	Three Point	10.67	78%	13.40	124%	46%
	y Axis					
Estimated Head/Torso Acceleration	Unsuspended	16.33	173%	20.26	239%	66%
	Mechanical	22.54	277%	28.54	377%	100%
	Four Point	27.84	366%	34.74	481%	115%
	Three Point	26.66	346%	33.49	460%	114%

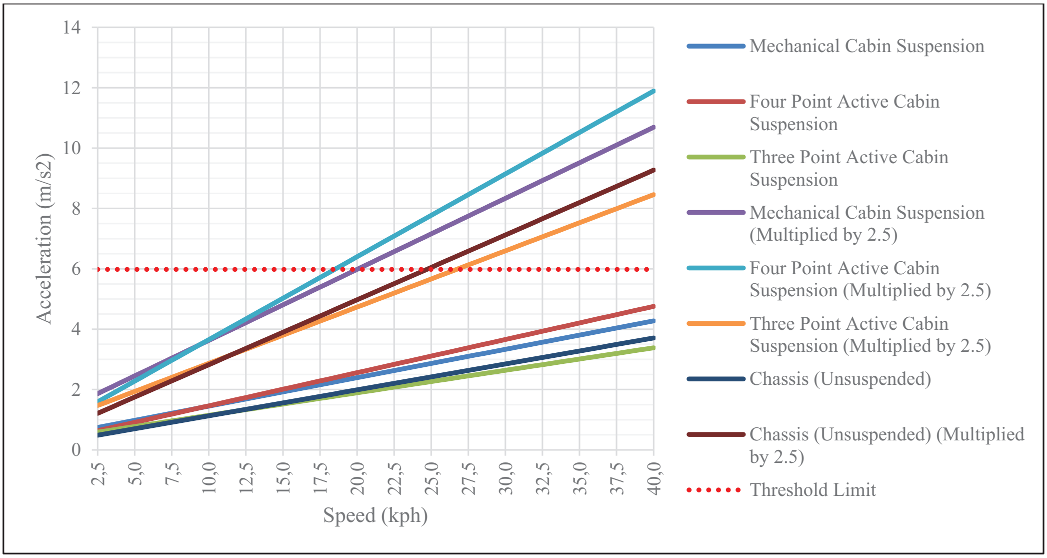

Figure 17. Chart showing the Estimated Acceleration in the *x* Axis

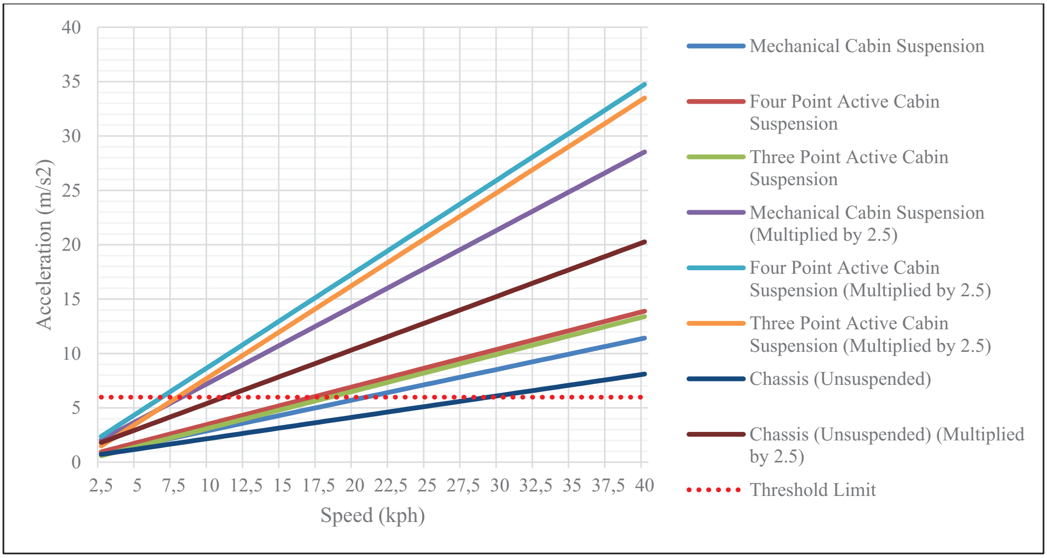

Figure 18. Chart showing the Estimated Acceleration in the *y* Axis

CONCLUSIONS

Surveys have shown that 58.0% of agricultural tractors operating in the North West of the UK, are not fitted with cabin suspension. Furthermore, the surveys have outlined that the agricultural tractors without cabin suspension complete the highest yearly operation (36.4%) in rough terrain conditions, when compared to the other cabin suspension systems considered.

Acceleration above 5.98 m/s^2, has the potential to cause damage to the fibres of the intervertebral discs. Data which has been collected shows that this limit is exceeded in the *y* axis between 2.5 and 30 kph for all of the cabin suspension considered in this report. Although, when the data is multiplied by 2.5 to estimate the acceleration experienced by the head/torso, this limit is exceeded in the *x* axis between 2.5 and 25 kph and exceeded in the *y* axis between 2.5 and 11 kph. Consequently, up to 62.0% of field activities have the potential for the operator to exceed the 5.98 m/s^2 threshold limit.

Only the estimated acceleration in the *x* axis, produced by the 3 point active cabin suspension is lower than the estimated acceleration produced by an unsuspended cabin, although this is only a reduction of 9.6% at 40 kph. All the other tested cabin suspension systems produce an increased level of acceleration when compared to an unsuspended cabin.

Moreover, the collected data has shown that acceleration in the *y* axis is up to 50.0% higher than acceleration measured in the x axis.

Therefore, to protect operators from exposure to acceleration in the *x* and *y* axis, improvements with regards to cabin suspension systems fitted to the cabin is required, due to exposure to acceleration having a degenerative effect on the operator's spinal structure (Waters et al., 2007; Bovenzi, 2006).

Concerns have been raised regarding the increase in operations speeds (32 to 40 kph) of agricultural tractors on public roads in the UK, due to a potential increase in the estimated acceleration of the head/torso in the *y* axis of 115.0%.

Furthermore, agricultural tractor operators, operating on private land are exempt from daily and weekly hour regulations, and therefore extended periods of exposure to acceleration could be encountered (up to 16.5 hours daily, during peak periods of the year) (Solecki, 2012).

Finally, Kim et al. (2018), states that currently the industry standard (ISO 2631), only requires the z axis to be suspended, even though this report has outlined that both the *x* and *y* axis have the potential to produce excessive levels of acceleration.

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