Assessment of risks in implementing automated satellite navigation systems

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Abstract

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One of the ways of increasing the efficiency and safety of work is the implementation of navigation systems in agricultural practice. Satellite navigation as a means of reducing the unit costs and increasing the safety can have a significant economic impact on a company when properly used. The objective of measurement was to assess the accuracy of a satellite system AutoTrack working with a correction signal SF2. Its provider specifies an accuracy of ± 5 cm for this signal type. The accuracy of machine work was compared for two scenarios, i.e. with and without satellite navigation. Further, the navigation of machines focused predominantly on AgGPS EZ-Guide Plus and AutoTrac Universal. The FMEA method was used to determine the risk of probable failures that can occur on machines while working. This work describes the individual failures that can occur on navigation systems of machines and analyses their impact on operator's safety.

Keywords: assisted steering; operator's safety; navigation accuracy; FMEA analysis

Occupational health and safety is an inseparable part of working and production activities. Safety is often perceived as a prevention of accidents, as measures leading to the elimination of accidents and health damage. However, a modern insight into this field is much broader. It defines a 'human factor', gives priority to a human being and his protection with respect to all the aspects associated with work (Hrubec et al. 2009). In connection with the protection of employees, it is required to deal with such factors as stress, workload, work monotony, working conditions, working relationships, etc.

Risk management is one of the tools, by means of which it is possible to increase the safety margin of various processes and specific activities. It enables the identification, assessment and reduction of risks (Pačiová et al. 2009).

When working with machines in agricultural practice, it is possible to encounter several aspects having an impact on safety. Individual types of threat that occur can influence not only operator's safety but can also have an environmental impact. At the same time, it need not be a sudden impact, but a progressive that occurs with failing to observe the basic rules, standards or laws (Macák, Žitňák 2010).

Frohman and Švarda (2010) describe the use of satellite navigation and RTK corrections in subsoiling. They indicate that using such operations within an effort to maintain competitiveness on the market appears to be more effective than the policy of buying larger machines and acquiring a larger area of agricultural land. McMahon (2003) describes the structure and benefits of assisted steering. He especially deals with the wireless transmission of

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application maps and recorded data directly from a field into a central computer. When determining the accuracy of satellite navigation of a tractor with implement, Ehsani et al. (2002) used an average error and standard deviation of machine trajectory error calculated from differences between an actual machine position in the field and a calculated (theoretical) position. They considered the efficiency comparison of six navigation systems with RTK GPS, as the theoretically most accurate system, to be the most reliable system of determining the accuracy of navigation systems.

An FMEA is an inductive (forward logic) failure analysis and is a core task in reliability engineering, safety engineering and quality engineering (Prístavka et al. 2011). A successful FMEA activity helps to identify potential failure modes based on experience with similar products and processes or based on common physics of failure logic (Bujna et al. 2012). It is widely used in development and manufacturing industries in various phases of the product life cycle (Bujna, Prístavka 2012). An effects analysis refers to studying the consequences of those failures on different system levels.

The objective of this work was to assess the risks associated with implementing the automated satellite navigation systems into a company by means of Failure Mode and Effects Analysis (FMEA). To make assessment the most effective, it was necessary to consider the accuracy of selected satellite navigation systems AutoTrack Universal and AgGPS EZ-Guide Plus. Subsequently, on the basis of the performed measurements and observed experience of operators and service workers, risks were assessed by means of the said FMEA.

MATERIAL AND METHODS

The assessment of AgGPS EZ-Guide Plus and AutoTrack Universal (both Deere & Company, Moline, USA) was performed on the basis of monitoring these systems when working in practical conditions. Based on practical experience and available manufacturer's guides, a network diagram with individual basic elements of a GPS receiver (StarFire iTC; Deere & Company, Moline, USA) (Fig. 1) was prepared. The network diagram was used as a background for creating the analysis of risk by means of FMEA.

The individual system elements (Fig. 1) were analysed using the FMEA method. After determining probable errors and reporting their impact on individual parts of the navigation system, we have searched for possible consequences and causes of these errors. The following part contained the determination of importance, probability and detectability of errors. After having determined the MR/P value (level of risk/priority), suitable corrective measures were suggested, and the risk number MR/P was specified again.

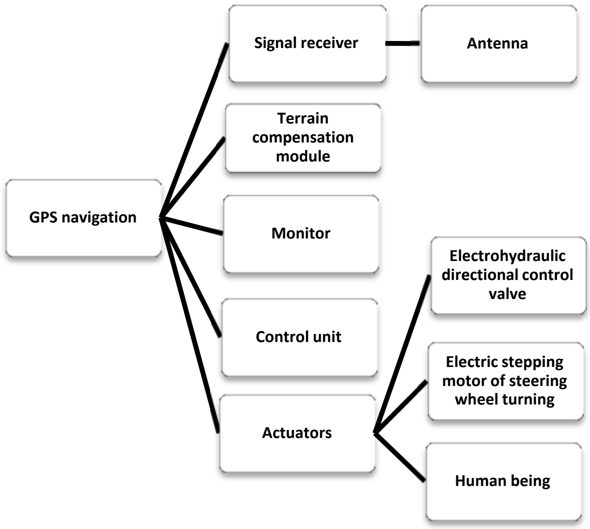

Fig. 1. Navigation system elements where failures are possible to occur

The table of FMEA analysis (Table 1) contains individual numerical values representing the risk number MR/P (*Vz* – severity, *Vy* – occurrence, *Od* – detection). The values *Vz*, *Vy*, and *Od* were determined according to the tables in STN ISO 9000 (2005).

To identify the risks, we have performed a number of measurements to determine the accuracy of navigation and to monitor the problems of operators with the navigation system as well as the benefits resulting from its implementation.

One of the said practical experiments was carried out in a field belonging to PD Rastislavice (farming cooperative), Slovak Republic. We measured there the accuracy of work of the automated satellite navigation system during soil loosening by a disc tiller. In this field, an experimental part was selected having an area of 9.51 ha, on which 213 monitoring points were distributed.

The machine (Kuhn Discovery XM 40; KUHN S.A., Saverne, France) performed shallow tillage after previous subsoiling and harvest of sugar beet. The basic technical parameters of the tractor and tiller Kuhn Discovery XM 40 are shown in Table 2.

The steering system is controlled by a steering system unit (SSU) (Deere & Company, Moline,

Table 1. FMEA form for assessment of failures

Serial No.	Failure location	Failure mode	Failure cause	Q	S	E	Consequences	*Vy*	*Vz*	*Od*	*MR/P*	Measures	*Vy*	*Vz*	*Od*	*MR/P*
1	signal receiver	short-term loss of signal	shielding of satellite signal	Y	N	Y	downtime, stress	6	5	3	90	maintenance of wind barriers	5	5	3	75
2	signal receiver	signal disturbance	effect of high voltage line	Y	N	Y	signal drop-out, worker's fatigue	4	4	3	48	working perpendicularly to line	3	4	2	24
3	signal receiver	neither differential nor correction signal	licence for differential signal expired	Y	N	N	no signal, downtime, stress	2	5	3	30	regular renewal of licence rights	1	5	3	15
4	terrain compensation module	position is occupied to the right or to the left	MTK is not calibrated	Y	Y	Y	error in navigation position	7	7	3	147	regular calibration	5	7	2	70
5	mobile processor	memory error	internal memory error	Y	N	N	system is unable to work	4	7	5	140	regular service and inspection of hardware	2	7	4	56
6	compensation module	MTK is unable to compensate changes in terrain	speed sensor does not respond	Y	Y	Y	inaccuracy of travels, effect on safety	6	7	4	168	regular service inspections	4	6	3	72
7	compensation module	MTK is able to correct neither position nor angle	heeling sensor is beyond range	Y	N	Y	inaccuracy of travels, effect on safety	6	6	6	216	regular inspection	4	6	3	72
8	monitor	parallel tracking system is slow or sluggish	incorrect update	Y	Y	Y	downtime, fatigue	4	6	5	120	setting of device	3	6	3	54
9	monitor	audible alarm does not sound	failure	N	Y	Y	late machine reversal by operators	4	3	3	36	inspection	3	3	3	27
10	monitor	display is blank or poorly visible	interrupted voltage	Y	Y	Y	reduced performance	3	6	4	72	inspection	2	6	3	36
11	monitor	display is not functioning correctly	problem with hardware	N	Y	N	reduced system safety	3	7	3	63	regular hardware tests	2	5	3	30
12	antenna	no communication with GPS receiver	GPS receiver or light bar are faulty	Y	Y	N	limitation of works, stress	4	7	3	84	using quality devices only	2	7	3	42
13	pc card	problem with data card	erroneous data card	N	N	N	delay of works	3	6	2	36	using quality memory media only	2	6	2	24
14	signal receiver	no communication with display	problem with can bus	Y	N	Y	device is unable to communicate with display	3	7	3	63	inspections	2	7	2	28

Table 1 to be continued

Serial No.	Failure location	Failure mode	Failure cause	Q	S	E	Consequences	Vy	Vz	Od	MR/P	Measures	Vy	Vz	Od	MR/P
15	mobile processor	device fails to accept the licence code	error in re-programming the product on card	N	Y	N	downtime, stress	4	7	4	112	training	2	7	2	28
16	monitor	overloaded display	absence of operator's knowledge	Y	Y	N	short-term system failure	3	4	4	48	increasing the awareness of operators	2	4	3	24
17	power supply	device is not activated after starting	damage of power supply due to vibrations	Y	Y	N	disabled works, stress	4	3	4	48	service inspections	2	3	3	18
18	control unit	vehicle deviates from travel direction	erroneous signal evaluation	Y	Y	Y	reduced quality of work	3	4	5	60	using a quality correction signal	2	4	5	40
19	electric stepping motor	steering wheel is skipping with automated guidance	rearrangement of drive on the steering wheel	Y	Y	Y	failure of automated guidance	3	6	4	72	using quality devices only	2	6	3	36
20	light bar	only one diode is shining on the bar	incorrect temperature in driver's cabin	Y	Y	Y	downtime, device damage	2	7	3	42	training	2	2	2	28

E –environment; S– safety; Q – quality; Y – yes, N – no; *Vy* – occurrence; *Vz* – severity; *Od* – detection; *MR/P* – risk number/priority; MTK – terrain compensation module

USA). This control unit collects information from individual components of the system, and signals pass from there into an electrohydraulic control valve ensuring tractor steering (turning of steering wheels). The substance of steering is in the fact that the electrohydraulic control valve doses the oil to double-action hydraulic cylinders so that the required direction of movement is maintained.

After passing of the machine, initial monitoring points were marked using marking pegs, from which the actual machine working width was measured using a metric gauge.

Navigation inaccuracies were recorded by measuring the implement width on worked soil after three passes of the machine, by which overlaps and skips were obtained, representing inaccuracies caused by a double navigation of the machine. In evaluation with this method, overlaps and double working width, which was set for navigation 4.8 m (Fig. 2a) and 5.2 m, were subtracted. Accuracy without satellite navigation was also measured. In that case, the machine was navigated based on experience and skills of operators. The measuring procedure with this method was identical with the previous one. With respect to the measuring method used, negative numerical values representing skips are actually overlaps (positive values).

RESULTS AND DISCUSSION

The disc tiller Kuhn Discovery XM 40 consists of two disc sections. The rear section of discs is wider than the front section by 0.35 m on each side. For the 4.8 m value set for navigation, multiple tillage was performed in certain parts of the field. Fig. 2a indicates that the navigated machine worked the dimensioned widths of right and left margins three times (i.e. in two passes, the area was worked once by the front section and two times with the rear section), thus creating an overlap of 0.7 m. For the given machine in this operation, the value of 5.15 m (Fig. 2b) represents an ideal value of spacing between neighbouring tramlines, which is entered into the satellite navigation system. There are no multiple overlaps, and an ideal areal machine capacity is ensured. For an optimum tillage with more plant residues (stubble etc.), it would be necessary to set the satellite navigation value to 5.00–5.10 m.

Fig. 3 illustrates a box-and-whisker plot representing the values of skips and overlaps for three passes of the machine with satellite navigation (Fig. 2). This

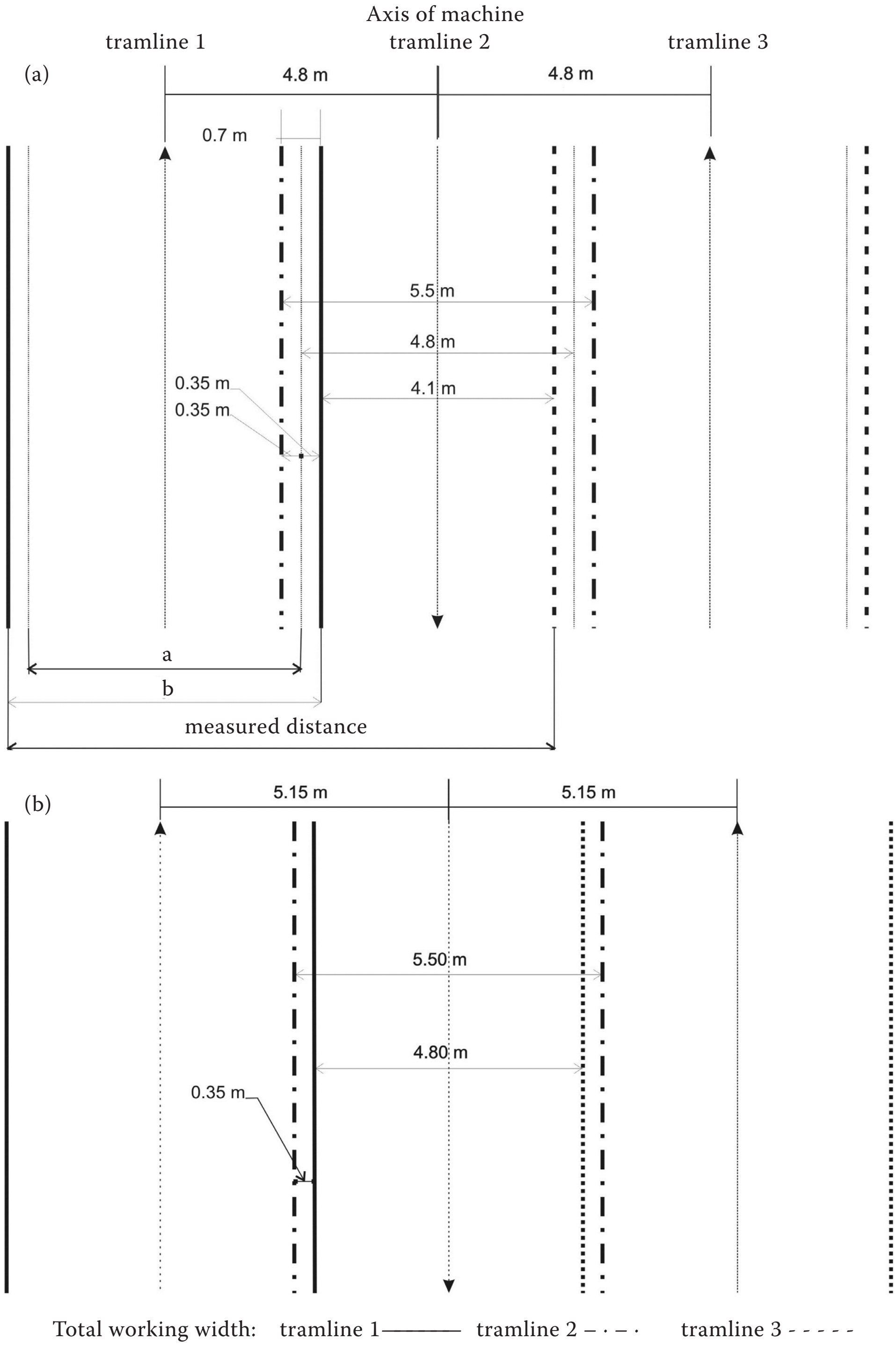

Fig. 2. Scheme of machine tramlines for navigation at (a) 4.8 m and (b) at 5.15 m
a –working width of first disc section; b – working width of second disc section (total working width of machine)

plot indicates a negative value of median equal to –0.06 m, which represents the mean value of the measured data. The plot further indicates the values of the upper and lower quartile; its interval of skips ranges from –0.01 m to –0.11 m. Without satellite navigation of the machine, half the values of skips ranged from –0.75 m to –0.93 m (Fig. 3).

With respect to the used measuring method, it should be noted that the presented results with a negative value actually represent a positive value, i.e. overlap.

For the performed field operation, it is possible to state that the used satellite navigation AutoTrack with the correction signal SF2 is sufficient in terms

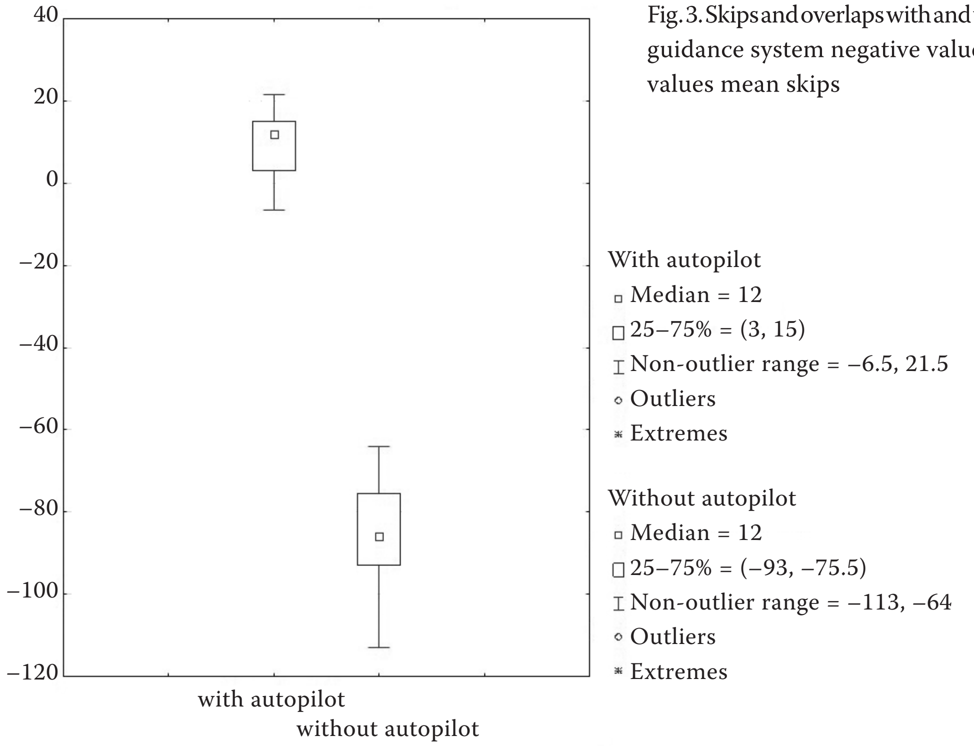

Fig. 3. Skips and overlaps with and without using the AutoTrack guidance system negative values mean overlaps, positive values mean skips

of agronomical requirements on tillage. An unnecessary large overlap occurred due to setting an incorrect value of working width for the satellite navigation system. Based on such experiments and failures recorded by machine operators and service workers, we determined the risks associated with using satellite navigation systems.

Procedure of FMEA application

After becoming sufficiently familiar with functions and work of machines using navigation systems, we used the FMEA analysis according to relevant criteria and consultations, and according to the selected methodology:
– identification of risks;
– identification of risks consequences;
– identification and analysis of risks causes;
– identification of risk level (quantifying the risk);
– determining corrective measures and re-quantifying the risk.

Evaluation of FMEA results (AgGPS EZ-Guide Plus and AutoTrack Universal)

By using the FMEA method, we were able to significantly reduce the value of risk on the examined navigation systems. After determining the importance, probability and detectability of a failure, and after subsequently quantifying the MR/P value, we have drawn the following conclusions.

The analysis gives us an overview of possible demonstrations and causes of failure that can occur when working with the navigation system. A significant point of the whole analysis was a proposal of safety measures to improve the existing situation. Before the evaluation of risks when working with the navigation of machines, it was necessary to know all the factors that can influence the safety of operators as well as legal regulations to be met by the system.

By determining the correct selection of safety measures, we reduced the most of revealed threats to an acceptable risk level. For the application of a similar analysis in practice, the implementation of this principle means a great success in terms of operators' safety at work. We found that exceeding values of risk are influenced especially by the absence of trained staff, regular renewal of licence agreements, regular maintenance and inspection of hardware and software, and using quality components of equipment. Every year, navigation systems bring new functions meaning a large obstacle for untrained staff. If operators do not know the system and there is an unexpected, banal, e.g. electronic or mechanical error that is easy to be removed and operators are unable to respond promptly, there is

Table 2. Basic technical parameters of machine

DISCOVER tiller XM 40		JOHN DEERE tractor 7820	
Working width (m)	4.75	engine output rating (ECE) (kW)	136
Max. working depth (mm)	220	max. engine output (ECE) (kW)	145
No. of discs (pcs)	40	transport Boost (ECE) (kW)	157
Disc diameter (mm)	660	No. of cylinders/volume (cm^3)	6TI/6,800
Working speed (km/h)	8–12	torsion moment flexibility (%)	45
Machine weight (kg)	4,290	max. speed (km/h)	40.0/50.0
Machine transport width (m)	2.45	power take-off (1/min)	540/540E/1,000
Required tractor power (kW)	132	hydraulics max. piston force (kN)	90.0

a time stress. In the long term, stress can have unfavourable effects on health and it is currently very underestimated. Last but not least, we shall not forget physical and sensory threats that were identified when assessing. Physical threats especially occur during the assembly of individual navigation components. An example can be mounting the receiver on the tractor's roof. Furthermore, there are various effects such as slipping when boarding, which is not directly connected with navigation but influences the safety of operators in terms of working environment. We shall not forget the sensory load which employees are constantly subjected to even though employers often pay no attention to that. Finally, there are other significant risks such as risk arising due to an incorrect ergonomy of workplace (worker is in an unfavourable position when spraying a high crop stand, causing spinal column pain). In the long term, these effects can be a starter of occupational diseases. Therefore, organizations should pay attention to possibilities of improving the process of farm machinery navigation. Individual manufacturers, such as, e.g. the Norac company (Saskatoon, Canada), offer technical solutions reducing the level of risk in certain threats.

Table 3. Highest values of risk number/priority (*MR*/*P*)

Failure location	Failure mode	*MR*/*P* before	*MR*/*P* after
		corrective measures	
MTK	position is occupied to the right or to the left	147	70
MTK	unable to compensate changes in terrain	168	84
MTK	able to correct neither position nor angle	216	72
Monitor	parallel tracking system is slow and sluggish	120	54
Mobile processor	device fails to accept the licence code	112	28
Mobile processor	memory error	140	56

MTK – terrain compensation module

In the prepared forms (Table 1), there are several indicators that show the resulting values of risk for individual components of the examined system. According to the evaluation, the highest risk level occurred in the terrain compensation module (MTK), which is the most important component to cover the undesired overlaps and skips on steep land. This error is often difficult to reveal; therefore, the value of the highest risk on this component represents number 216 (Table 3). The relevant corrective measures (Table 1) give an overview of how to avoid the individual failures.

Table 3 contains the system components with the highest risk number. It is possible to see how the risk value declined on the most risky parts of the system. The risk value was reduced by about one half, and this value can be considered a controllable risk. With these navigation system components, a high risk level before measures was and often is caused by absence of knowledge. The problem of a company that decides to use the satellite navigation of machines is especially the absence of perfectly qualified personnel.

In our case, failures with the highest risk number represent 30% of the total possible examined components on which failures of a certain extent are possible to occur. The remaining 70% are negligible failures because their values do not exceed risk number 100. However, also with these negligible failures were we able to reduce the risk by one half. That can be considered as very successful in practical applications.

In conclusion, it can be stated that using navigation in machines has a positive effect on the facilitation of work and reduction of fatigue; however, an efficient management of work is necessary.

Our analysis focused on failures of GPS navigation, by which we obtained valuable information on possible failures and the mode of their detection. When applying the FMEA method, a too high risk number forced us to consider suitable corrective measures.

As already mentioned, the individual forms contain described consequences such as safety, stress, fatigue, which are directly or indirectly influenced by navigation itself. When working with mobile machines and energy sources, operators are influenced primarily by the working environment. The role of navigation is to alleviate some negative consequences of the working environment; however, not always are we able to reduce these consequences by GPS.

When performing the individual working operations, operators are under sensory stress which is caused by a continuous monitoring of display and control elements. Sensory stress can best be seen in the system working on the principle of a light bar, where the vision of operators is loaded with monitoring the diodes on the panel of the light bar. Therefore, such being the case, the use of automated navigation with a stepping motor appears to be a better solution. An important factor for operator's comfort is the distribution of individual display and control elements of navigation. This issue is described in the Decree No 542/2007 on details of occupational health protection against physical stress, mental stress and sensory stress.

Using navigation, operators can be under a considerable stress. That occurs when operators are not trained and have not a perfect knowledge of controlling the system. There is often a failure that cannot be easily and quickly removed, and service workers must be called. By waiting on service workers, working hours can be extended, and the total downtime can be prolonged, which is undesirable for operators, especially when they are paid according to output. The reduction of negative impacts of stress on operators and working process can be achieved by preventive maintenance.

After reviewing the said facts, it can be stated that the use of navigation systems appears to be a suitable method for facilitating the work. To maintain this trend and in order for the operator not to be under an excessive mental stress, the suitability of using the above-mentioned FMEA is at the right place, especially when the objective is to save time and investments that are not negligible when implementing the GPS navigation.

CONCLUSION

This contribution focuses on the safety of navigation systems in a company. The use of navigation systems and navigation equipment in mobile machines working in fields appears to be the right response to increase the safety and reduce the potential environmental impacts. The implementation of satellite navigation increases the overall productivity of work and reduces the fatigue of workers. We know that the current market is enriched by growing complexities of machines and technologies, by which the probability of risk increases. Therefore, it is important that attention is paid to occupational health and safety. The responsibility for the concept and policy of occupational health and safety lies on the employer. The thing that matters and which the employer must not forget is training. In order to increase the overall efficiency of using navigation systems, the worker must be provided with relevant information on possible failures of navigation systems.

When using navigation, it is necessary to be aware of individual unfavourable impacts on operators such as a poor organisation of work and failing to observe the preventive maintenance. Decision to use GPS and apply the FMEA method can positively influence the whole farm. By a preventive application of FMEA, it is possible to avoid problems that often occur when applying new technologies.

The result of function of the entire system is a more accurate and comfort control of driving direction, which leads to reduction of the load, fatigue and stress of operators. That contributes to increasing safety of working with machines, which was confirmed by a driver of the measured machine, too. Other benefits of satellite navigation systems with an autopilot are the possibility of working at night, in fog, and in dusty conditions, i.e. by observing the required spacing of tramlines, increased quality of work (overlaps, skips, headlands, etc.), and limiting the environmental damage.

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