Comparative risk assessment of vehicle maintenance activities: Hybrid, battery electric, and hydrogen fuel cell cars

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A B S T R A C T

In this research, vehicle maintenance activities and their safety risks were statistically analyzed. This study focused on three types of vehicle: hybrid, battery electric, and hydrogen fuel cell cars. The repair activities and the risks for each power train technology were identified by a panel of experts. Depending on its frequency and severity, risk values were calculated for each maintenance activity. The method chosen was the staticized group method, which involves collection opinions from a panel of experts. The ten experts finally chosen were asked to anonymously respond to a survey that had been especially designed to reduce bias and ensure the quality of the data. The most dangerous vehicle maintenance activities were the manipulation of asbestos, charging and discharging of high value capacitors, and welding.

Relevance to industry: The results of this research reflect the urgent need for workers in the automobile sector to be trained for emerging risks in new technologies.

1. Introduction

In 2011, there were more than one billion motor vehicles in use in the world (Sousanis, 2011). For this reason, vehicle maintenance is an extremely important sector of economic activity. Nevertheless, despite its prominence, surprisingly little attention has been paid to the occupational health and safety conditions of mechanics and other workers at vehicle maintenance worksites. In fact, according to the Bureau of Labour and Statistics (BLS, 2011), workers in this sector had higher rates of occupational injuries and illnesses in comparison to workers from other sectors. During 2011, the number of non-fatal injuries and illnesses per 100 full-time vehicle repair workers in the United States of America was 3.9, whereas in other sectors such as chemical manufacturing or mining support activities, the number was 2.4 and 2.3, respectively.

This high accident rate has a wide range of causes and stems from multiple variables. For example, there are various stressors at the vehicle maintenance worksite, which include the following: (i) a noisy environment (Bejan et al., 2011; Dembe et al., 2005; Sorock et al., 2004); (ii) asbestos (Dotson, 2006; Cohen and Van Orden, 2008; Blake et al., 2008); and (iii) ergonomic conditions (Fredriksson et al., 2001; Vandergrift et al., 2011).

Although vehicle mechanics are exposed to a wide range of occupational risks, previous research has only focused on one risk type, and has not provided a comprehensive overview of the issue. More concretely, majority of the previous studies have centered on conventional combustion. However the rapid development and expansion of emerging automobile technologies has produced new occupational health and safety risks, which must also be considered.

Mechanics and workers employed in garages and repair shops generally have an elementary school education or have never finished high school. Many of them began working as apprentices and were trained on the job by more experienced staff. As a result, most of their skills were acquired on the job in practical "hands-on" contexts without any theoretical training (Barber, 2004; Hager, 1998). The recent appearance of new car technologies signifies that there is currently a scarcity of experts familiar with the unique design and characteristics of these vehicles. This lack of skilled personnel is a problem for the manufacturing and maintenance of these vehicles, but it is also a problem from the perspective of occupational health and safety.

This research study calculated the safety risk of various repair activities for these new types of vehicle. In this regard, the maintenance of hybrid, battery electric, and hydrogen fuel cell cars were analyzed with the binary method as well as the staticized group method.

2. Methodology

Within the framework of this research, a specific risk assessment method was selected, based on the results of previous studies. In the construction sector, there are currently several risk quantification methods of varying levels of complexity and application. For example, Everett (1999) studied ergonomic risks pertaining to 65 construction activities and rated each risk factor on a three-point scale (*insignificant*, *moderate*, and *high*). The objective of his study was to identify risks leading to injuries from overexertion.

The concept of *safety risk* is defined as the product of the frequency and severity by various authors (Sun et al., 2008; Baradan and Usmen, 2006). Hallowell et al. (2011) and Jannadi and Almishari (2003) used a similar quantification method though enhanced with the component of exposure. The research study described in this paper used the binary method (British Standard Institution, 1996), in which unit risk is also the product of frequency and severity. *Frequency* is expressed in terms of worker hours per incident, whereas severity is defined in terms of impact to the worker per incident.

$$\text{UNIT RISK}\left(\frac{\text{severity}}{\text{work-hour}}\right) = \text{Frequency}\left(\frac{\text{incident}}{\text{work-hour}}\right) \times \text{Severity}\left(\frac{\text{severity}}{\text{incident}}\right) \quad (1)$$

After specifying the method of risk quantification, the next step was the selection of a suitable strategy to accomplish our research objectives. The two considered were the staticized groups research method and the Delphi method. The staticized group technique is similar to the Delphi method but differs from it in that it does not include feedback or iterations. When comparing the accuracy of both methods, various studies have reported that the staticized group method is more accurate than the Delphi method (Best, 1974; Rowe and Wright, 1996), whereas other research found no substantial difference in the accuracy of the two methods (Fischer, 1981; Sniezek, 1990). According to other studies, however, the Delphi method was found to be less accurate when there were many iterations (Gustafson et al., 1973; Boje and Murnighan, 1982).

According to Erffmeyer and Lane (1984), the staticized group approach is preferable because panel members are less likely to arrive at a consensus on an incorrect value. Based on Erffmeyer and Lane (1984) as well as the previous research cited, the staticized group was thus considered to be the most suitable method for our study.

2.1. Panel members

In staticized groups, a key factor in the quality of the study is the selection of the experts. According to Hallowell and Gambatese (2010), the level of expertise is the most important facet of a panel member. They thus provide a set of guidelines that include a flexible point system for the selection of expert panel members. This point system was taken and adapted to the purposes of our study. Table 1 shows the modified version of the point system, which was used to choose our panel of experts.

The authors contacted 30 international experts in occupational safety risk with experience in the automobile sector. After a review of the background and availability of these candidates, fourteen of them were pre-selected. These candidates came from eight high-profile companies in the automobile sector and four university engineering schools. In addition to the flexible point system requirements, only one expert per company or per university was selected in order to ensure diversity.

Table 1
Flexible point system for the selection of panel members.

Education and experience	Points
Bachelor in Engineering	4
Master in Engineering	6
Mechanical or electric background	3
PhD in Engineering	4
Master in Occupational Risk Prevention	4
Professional registration	3
Years of professional experience	1
Papers published in ISI journals	2
Author of a book in the field	4
Faculty member of an accredited university	3

All panel members met the requirements in the guidelines proposed by Hallowell and Gambatese (2010), which meant that they scored a total of at least eleven points in four or more education or experience categories. Nevertheless, of the fourteen pre-selected candidates, there were ten that were finally chosen as the most suitable. The other four professionals were thus excluded from the panel.

The qualifications of the panel members were the following:

- **Master's Degree in Occupational Risk Prevention**. All panel members had this degree, which guaranteed their expertise in safety at work and occupational risk. This was found to be the most valuable qualification because it meant that the panel member had high-level training in occupational health and safety and thus possessed the necessary level of expertise to evaluate risks in vehicle maintenance.
- **Bachelor's/Master's Degree in Engineering**. This degree assured that the members had the necessary background in engineering. This was clearly relevant because automobile repair activities for new types of vehicle involve cutting-edge technology, and only by being familiar with technical issues could panel members make accurately evaluate the risks involved.
- **Extensive professional experience**. Between them, the panelists had a total of 96 years of experience in the automobile sector. These years of experience allowed panel members to assess risks on the basis of what they had actually seen at the workplace.

2.2. Research design

In order to obtain information regarding risk levels, a web-survey was designed and made available to the experts. The survey was limited to panel members, who were given a password to access the site. The web-survey expired after all the data were collected in the stipulated time period.

The following strategies were used to optimize experimental design and eliminate bias:

- The order of the questions and the potential safety risks in the survey were randomized for each panel member. This reduced the contrast effect as well as the primacy effect.
- Independent frequency and severity rates were implemented.
- The anonymity of each expert was ensured.

2.3. Survey design and content

The survey was initially divided into four vehicle maintenance categories. The first three categories were for vehicles powered by emerging technologies, and the fourth category referred to general vehicle repairs. Each of these categories was further divided into two subcategories: (i) activities and (ii) safety risks (Table 2).

The inventory of activities and safety risks was extracted from previous studies as well as from the repair manuals of car companies (CESVIMAP, 2003; Olszewski, 2011; Mitsubishi Motors Co., 2011; Nissan Motor Corporation, 2010; Toyota Motor Corporation, 2007; Honda Motor Company, 2005). These activities were evaluated by the expert panel in accordance with the binary method guidelines of the British Standard BS8800 (British Standard Institution, 1996). Experts were asked to give each activity a risk value ranging from 1 [Trivial Risk] to 5 [Intolerable Risk], taking into account the frequency of the risk and its severity in case of accident (Tables 3 and 4).

In regards to the safety risk, the panelists were asked to give their opinion on frequency rates and severity levels based on the scale in Tables 5 and 6. These scales, as formulated by Hallowell and Gambatese (2009), cover a wide spectrum of frequency and severity levels.

The scores for the safety risks were obtained by converting the frequency ratings from a range of values with units of incident per worker-hour and then multiplying them by the values on the severity scale (Hallowell and Gambatese, 2010). For example, if the expert rated the average frequency as 100–1000 w-h/incident, the mean value of 550 w-h/incident was identified and the inverted value 0.0018 (1/550 incident/w-h) was regarded as the frequency value for the risk and activity. The product of this frequency and severity rating, which ranged from 1 to 26.124, was the unit risk for the safety risk.

Then, experts were asked to evaluate the activities and risk according to their experience and knowledge for the most common working conditions, not according to the best or the worst conditions possible.

3. Results and discussion

3.1. General vehicle repair activities

In this subcategory, general vehicle maintenance operations not linked to a specific technology (e.g. car body, painting, and glasswork) were evaluated with the binary method guidelines of the British Standard Institution (1996). A total of 17 activities were studied by the experts.

As can be observed in Table 7, the most dangerous activity was handling asbestos. Although this problem is hardly a new one (Rohl et al., 1976), it has still not been solved (Blake et al., 2008; Kakooei and Marioryad, 2009). Welding operations were also given a high score. In contrast, glasswork, cleaning of car parts, measurements, tune-ups, and inspections had the lowest values. Table 8 includes results about safety risk.

Table 2
Vehicle maintenance technology.

Maintenance category	Subcategories
Hybrid vehicle repairs	Activities
	Safety risk
Battery electric vehicle repairs	Activities
	Safety risk
Hydrogen fuel cell vehicle repairs	Activities
	Safety risk
General vehicle repairs	Activities
	Safety risk

Table 3
Risk level matrix.

		Severity		
		Slight	Harmful	Extremely harmful
Probability	Highly unlikely	Trivial risk (1)	Tolerable risk (2)	Moderate risk (3)
	Unlikely	Tolerable risk (2)	Moderate risk (3)	Substantial risk (4)
	Likely	Moderate risk (3)	Substantial risk (4)	Intolerable risk (5)

3.2. Hybrid vehicle technologies

In regards to hybrid technologies, safety risks were also assessed by the panel of experts (Table 9). Activities were evaluated by assigning a single value as the risk score for each activity (British Standard Institution, 1996), whereas the safety risk was calculated as the product of the frequency value and severity rating (Hallowell and Gambatese, 2009). The assembly/dismantling of the engine/electric generator and the assembly/dismantling of the transmission system were the two activities with the highest

Table 4
Risk level values.

Risk level	Score value
Trivial risk	1
Tolerable risk	2
Moderate risk	3
Substantial risk	4
Intolerable risk	5

Table 5
Frequency scale.

Worker hours per incident	Frequency score
>100 million	1
10–100 million	2
1–10 million	3
100,000–1 million	4
10,000–100,000	5
1000–10,000	6
100–1000	7
10–100	8
1–10	9
0.1–1	10

Table 6
Severity scale.

Subjective severity level	Severity score
Negligible	1
Temporary discomfort	2
Persistent discomfort	4
Temporary pain	8
Persistent pain	16
Minor first aid	32
Major first aid	64
Medical case	128
Lost work time	256
Permanent disablement	1024
Fatality	26,214

Table 7
General car repair activities.

Activity	Risk score	Median	Standard deviation
Handling of asbestos	4	4	1.054
Oxyacetylene welding	3.3	3	0.674
Resistance welding	3.2	3	0.788
Other welding methods	3.1	3	0.737
Handling of fuel tanks	3.1	3	0.994
Handling and cutting of sheet metal	2.9	3	0.875
Handling of airbags	2.9	3	1.100
Mechanical and thermal sheet iron repair	2.6	2.5	0.699
Assembly and dismantling operations	2.3	2	0.674
Handling of paints, cleaning of surfaces	2.2	2	0.788
Sanding operations	2.1	2	0.737
Paint application	2	2	0.816
Plastic repair	1.9	2	0.994
Charging and discharging of circuits	1.9	2	0.875
Glasswork	1.8	2	0.421
Cleaning of car parts	1.8	1.5	0.918
Measurements, tune-ups, and inspections	1.3	1	0.483

Table 8
Risk scores of general repair.

Safety risk	Risk score
Being struck with tools and equipment	0.582
Exposure to harmful substances	0.291
Noise	0.145
Dermatitis	0.116
Overexertion	0.058
Fall from height	0.018
Splashing	0.007
Airborne particles	0.006
Cutting	0.002
Burning	0.002
Electric shock	0.002
Fall at the same level	0.001
Thermal stress	0.001
Radiation	0.001

scores. On the other hand, the checking of the liquid refrigerant had the lowest value.

The safety risk associated with battery terminals received the highest score (Table 10). In this hybrid vehicle maintenance, the frequency of short-circuit risk is high. Evidently, an undesired contact can easily occur since the work is carried out with metal tools. In contrast, risk of explosion, fire, and toxic smoke obtained the lowest score. Despite the fact that this type of risk has a high value on the severity scale, its frequency score is very low. As corroborated by the experts, the risks associated with batteries in hybrid technologies are basically the same as those in battery electric vehicles. Consequently, these results are valid for both technologies.

Table 9
Hybrid vehicle maintenance activities.

Activity	Risk score	Median	Standard deviation
Assembly/dismantling of the engine/electric generator	3.1	3	0.567
Assembly/dismantling of the transmission system	2.7	3	0.674
Checking of the electric isolation of the engine	2.3	2.5	0.823
Repair of mechanical car parts	2.3	2	0.483
Checking of electric resistance coil	2.1	2	1.100
Checking of hybrid transmission oil	1.9	2	0.737
Reconstruction of joints	1.7	2	0.674
Checking of liquid refrigerant	1.6	2	0.516

Table 10
Risk scores for hybrid vehicle maintenance.

Safety risk	Risk score
Battery terminals, short-circuit risk	0.486
Battery terminals, electric-arc risk in wet environments	0.476
Exposure to chemical substances	0.259
Temperature of materials	0.245
Battery temperature	0.234
Battery weight	0.070
Vapors from battery	0.059
Electrolyte projections	0.023
Explosion, fire, toxic smoke	0.002

3.3. *Battery electric vehicle technologies*

Five activities and fifteen safety risks were studied for battery electric automobiles. The results in Table 11 show that the lifting vehicles with traction batteries were considered the most dangerous activity, whereas the visual inspection of the traction battery was given the lowest score.

According to the expert panel (Table 12), electric shock during repair was the most dangerous safety risk (risk score = 0.672). However, the risk of electric shock at the beginning of the repair process was considered significantly lower (unit risk score = 0.019) than during subsequent maintenance phases. When asked about this difference in scores for the same risk, experts claimed that the maintenance and repair procedures of the manufacturers (Mitsubishi Motors Co., 2011; Nissan Motor Corporation, 2010; Toyota Motor Corporation, 2007; Honda Motor Company, 2005) clearly specify how to disable electrical systems at the beginning of the repair process. Consequently, the electrical risk at the beginning of maintenance is low. However, later on, this risk dramatically increases because mechanics may unexpectedly come in contact with damaged electrical equipment.

According to the experts, the risk of being struck by a car in movement is very high in the repair of battery electric cars. Although excess noise is often a stressor in vehicle maintenance, the absence of noise can also be a problem because electric engines are so silent that they give no warning when the car is approaching.

3.4. *Maintenance activities of hydrogen fuel cell vehicles*

Twelve activities and ten safety risks for hydrogen were identified for hydrogen fuel cell cars (Table 13). The installation/removal of liquid hydrogen tanks received the highest risk score (3.3). Other activities such as the checking and repairing of hydrogen losses (risk score = 3.1) and the installation/removal of hydrogen gas tanks (risk score = 2.9) were considered to have a similar level of risk in the opinion of the panel members. On the other hand, the

Table 11
Battery electric vehicle maintenance activities.

Activity	Risk score	Median	Standard deviation
Lifting of vehicles with traction batteries	2.7	2.5	0.823
Testing of electrical circuits, short search, referrals, and grounding inspection. Testing voltage peak	2.6	2	1.074
Checking of the voltage in the vehicle	2.3	2	0.948
Testing of connectors	2.2	2	0.918
Visual inspection of the traction battery	1.9	2	0.875

Table 12
Risk scores for battery electric vehicle maintenance.

Safety risk	Risk score
Electric shock caused by unexpected damaged component during repair procedures	0.672
Electric shock caused by wiring of high voltage	0.579
Being struck by moving cars with silent engines	0.571
Electric shock caused by fire extinction with water	0.499
Electromagnetic risk for pacemaker	0.373
Electric shock caused by the removal of high-voltage service switch	0.354
Electric shock while downloading high-density capacitor	0.288
Electric shock activating the H/T system for timers start of charging or A/C	0.233
Electric shock caused by auxiliary battery disconnection in the process of loading	0.122
Airbags, risk of activation after disconnection from the H/T system	0.119
Electric shock caused by damaged traction batteries	0.059
Electric shock caused by machine diagnostic connector (SAE J1962)	0.026
Electric shock at beginning of repairs	0.019
Traction batteries damaged, exposure to chemicals	0.005
Traction batteries damaged, splashing at high temperatures	0.002

checking and repairing of the ground connection from circuit hydrogen (risk score = 2) and the testing and calibration of sensors for detecting hydrogen (risk score = 1.9) were given the lowest values.

As occurred with battery electric vehicles, the safety risks linked to electric shock were regarded as the highest risks (Table 14). Electric shock from the fuel cell obtained the highest score (0.524). In contrast, air condensation in the valves had the lowest one (0.008).

3.5. Comparison of results

As can be observed in the scores from Table 15, the highest-risk activities were the handling of asbestos, and welding, respectively. These activities are classified as general repair procedures since they are associated with combustion engines. Regarding activities specific of emerging technologies, the installation/removal of liquid hydrogen tanks and the assembly/dismantling of engine/electric generators are third and fifth on the list.

Table 16 ranks the safety risks for vehicle maintenance activities. The greatest safety risk during this research was found to be electric shock during the repair of battery electric cars (risk score = 0.672). The next most serious risk was being struck with tools and equipment (a general repairs activity) though this risk had a somewhat lower value of 0.582. As can be observed, the third greatest risk was being struck by moving cars with silent engines. However, this is not only a danger for mechanics at the vehicle maintenance workplace, but also for pedestrians and cyclists on the road. Fifth on the list is the first safety risk linked to hydrogen fuel cell cars, electric shock in the fuel cell, with a score of 0.524.

Table 13
Maintenance activities for hydrogen fuel cell vehicles.

Activity	Risk score	Median	Standard deviation
Installation/removal of liquid hydrogen tanks	3.3	3	0.674
Checking and repair of hydrogen losses	3.1	3	0.875
Installation/removal of hydrogen gas tanks	2.9	3	0.737
Checking of the internal damage deposit	2.8	3	0.788
Presence of air in hydrogen repaired circuits	2.7	3	0.948
Checking and replenishment of the liquid refrigerant in the battery	2.6	2.5	0.966
Checking and repair of the air filter of the battery	2.3	2	0.948
Checking of external tank damage	2.3	2	1.059
Checking and repair of the fan stack	2.2	2	0.632
Cleaning of tanks with soaps/solvents	2.2	2	1.032
Checking and repair of the ground connection from circuit hydrogen	2	2	0.471
Testing and calibration of sensors for detecting hydrogen	1.9	2	0.737

Table 14
Risk scores for hydrogen fuel cell vehicle maintenance.

Safety risk	Risk score
Electric shock in the fuel cell	0.524
Grounding of the hydrogen circuit, static electricity	0.497
Liquid hydrogen tanks, evaporation of hydrogen atmospheres	0.495
Explosive atmospheres	0.378
Liquid hydrogen tanks, freezing, cryogenic burns, hypothermia	0.233
Hydrogen tanks (gas and liquid) leak	0.206
Battery terminals, arc flash hazard in high humidity environments	0.100
Hydrogen fires (flames are transparent)	0.028
High concentrations of hydrogen and oxygen displacement, asphyxia	0.012
Liquid hydrogen tanks, air condensation in the valves	0.008

As can be observed in scores from Table 17 general repairs and hydrogen fuel cell technologies obtained the highest total risk scores of their activities. Similarly, they obtained the highest averages risk scores per activity. On the opposite, hybrid and battery electric obtained the lowest values. Although differences between total risk values were important, the differences between averages per activity were low.

4. Conclusions

The risk values obtained in this research can be used as a tool to assess risks in automobile repair workshops. Emerging technologies and vehicle maintenance worksites bring new safety issues to the forefront, which are the result of using new equipment, devices and tools. The safety topics discussed in this paper can facilitate risk management in vehicle maintenance activities. As for preventive measures, resources are always limited and thus must be managed efficiently. The managers and supervisors of automobile workshops must first identify the most dangerous activities and their risks to worker safety and health. This is the first step in prioritizing preventive measures, based on a coherent scale of needs.

The classification in our study, as based on the scores given by expert panel members, places the following activities at the top of the safety risk list: electric shock during repair, wiring of high voltage, being struck by moving cars with silent engines, and electric shock from the fuel cell. Accordingly, special attention and effective preventive measures are urgently needed to reduce these safety risks. Special training as well as the elaboration of detailed protocols are effective ways of preventing electric shock during the repair and wiring of high voltage. Depending on the electric power of the automobile, different skills and qualifications should be required of the workers. In consequence, only authorized workers who have received suitable training in electricity should be exposed to the risk associated with this type of maintenance activity. In regards to the danger of workers being stuck by moving cars with silent engines, an obvious preventive measure would be to install a noise source that would warn people when the car was approaching.

Similarly, the handling of asbestos, welding activities, assembly/dismantling of the engine/electric generator, and the installation/removal of liquid hydrogen tanks were all evaluated as high-risk

Table 15
Risk scores for vehicle maintenance activities.

N°	Activity	Risk score	Car technology
1	Handling of asbestos	4	General repairs
2	Oxyacetylene welding	3.3	General repairs
3	Installation/removal of liquid hydrogen tanks	3.3	Hydrogen fuel cell
4	Resistance welding	3.2	General repairs
5	Assembly/dismantling of engine/electric generators	3.1	Hybrid
6	Other welding methods	3.1	General repairs
7	Handling of fuel tanks	3.1	General repairs
8	Checking and repair of hydrogen losses	3.1	Hydrogen fuel cell
9	Handling and cutting of sheet iron	2.9	General repairs
10	Handling of airbags	2.9	General repairs
11	Installation/removal of hydrogen gas tanks	2.9	Hydrogen fuel cell
12	Checking of the internal damage deposit	2.8	Hydrogen fuel cell
13	Assembly/dismantling of transmission system	2.7	Hybrid
14	Lifting of vehicle with traction batteries	2.7	Battery electric
15	Presence of air in hydrogen repaired circuits	2.7	Hydrogen fuel cell
16	Mechanical and thermal sheet iron repair	2.6	General repairs
17	Testing of electrical circuits, short search, referrals, grounding inspection. Testing of voltage peak	2.6	Battery electric
18	Checking and replenishment of liquid refrigerant	2.6	Hydrogen fuel cell
19	Assembly and dismantling operations	2.3	General repairs
20	Checking of engine electric isolation	2.3	Hybrid
21	Repair of engine parts	2.3	Hybrid
22	Checking of the electric resistance coil	2.3	Hybrid
23	Checking of the electrical current in the vehicle	2.3	Battery electric
24	Checking and repair of the battery air filter	2.3	Hydrogen fuel cell
25	Handling of paint, cleaning of surfaces	2.2	General repairs
26	Testing of connectors	2.2	Battery electric
27	Checking of external tank damage	2.2	Hydrogen fuel cell
28	Checking and repair of the fan stack	2.2	Hydrogen fuel cell
29	Sanding operations	2.1	General repairs
30	Paint application	2	General repairs
31	Cleaning of tanks with soaps/solvents	2	Hydrogen fuel cell
32	Checking and repair of the ground connection and of the hydrogen circuit	2	Hydrogen fuel cell
33	Plastic repair	1.9	General repairs
34	Charging and discharging of circuits	1.9	General repairs
35	Checking of hybrid transmission oil	1.9	Hybrid
36	Visual inspection of the traction battery	1.9	Battery electric
37	Testing and calibration of sensors for detecting hydrogen	1.9	Hydrogen fuel cell
38	Glasswork	1.8	General repairs
39	Cleaning of vehicle parts	1.8	General repairs
40	Reconstruction of joints	1.7	Hybrid
41	Checking of liquid refrigerant	1.6	Hybrid
42	Measurements, tune-ups, and inspections	1.3	General repairs

activities. Even though the risks stemming from asbestos could easily be dealt with by prohibiting its use in automobiles, in certain countries, this material is still allowed, and thus, it is a component of many vehicles. Alternatively, material-specific protocols could be implemented that would improve the occupational health and safety levels of the workers who must handle asbestos. In the same way, specific procedures for the installation or removal of liquid hydrogen tanks as well as an ATEX evaluation would improve the safety of these activities.

It cannot be concluded that one technology is safer than other one because results do not include workers exposure, but activities of maintenance in hydrogen fuel cell cars obtained the highest scores per activity, and this could mean highest risk for this emerging technology if the exposure values of the workers were similar to other technologies.

The design and implementation of these and other preventive measures that would decrease risks and thus have a positive impact on the occupational health and safety in the vehicle maintenance sector will be the focus of future.

4.1. *Limitations of the study*

One of the limitations of this study was that it did not include the exposure (worker-hours) to the hazards. Evidently, the total risk value depends on the magnitude and length of exposure. This is directly related to the work schedule of mechanics and the distribution of tasks in the workshop.

$$\text{TOTAL RISK}(\text{severity}) = \text{Frequency}\left(\frac{\text{accident}}{\text{work-hour}}\right) \times \text{Severity}\left(\frac{\text{severity}}{\text{accident}}\right) \times \text{Exposure}(\text{work-hour}) \quad (2)$$

If the exposure is low, but the unit risk is high, then the total risk may be low compared to the exposure of the workers to other activities. Similarly, if the exposure is high but the unit risk is low, then the total risk may be high in comparison to the other activities. Since exposure data would improve the accuracy of the results, it will be a factor considered in further researches.

Other limitation of the research was that risk levels have been evaluated for the case of a common mechanic worker. Specific factors with possible influence in the frequency and severity of accidents as training, age, gender, experience and others were not possible to be considered due to the general scope of the research. Specific factors should be considered in specific future studies.

Table 16
Ranking of safety risks associated with emerging vehicle technologies.

N°	Safety risk	Risk score	Car technology
1	Electric shock caused by unexpected damaged component during repair procedures.	0.672	Battery electric
2	Being struck with tools and equipment	0.582	General repairs
3	Electric shock caused by wiring of high voltage	0.579	Battery electric
4	Being struck by moving cars with silent engines	0.571	Battery electric
5	Electric shock in the fuel cell	0.524	Hydrogen fuel cell
6	Electric shock caused by fire extinction with water	0.499	Battery electric
7	Grounding of the hydrogen circuit, static electricity	0.497	Hydrogen fuel cell
8	Liquid hydrogen tanks, evaporation of hydrogen atmospheres	0.495	Hydrogen fuel cell
9	Battery terminals, short circuit risk	0.486	Hybrid
10	Battery terminals, electric arc risk in wet environments	0.476	Hybrid
11	Explosive atmospheres	0.378	Hydrogen fuel cell
12	Electromagnetic risk for pacemaker	0.373	Battery electric
13	Electric shock caused by the removal of high-voltage service switch	0.354	Battery electric
14	Exposure to harmful substances	0.291	General repairs
15	Electric shock while downloading high-density capacitor	0.288	Battery electric
16	Exposure to chemical substances	0.259	Hybrid
17	Temperature of materials	0.245	Hybrid
18	Battery temperature	0.234	Hybrid
19	Liquid hydrogen tanks, freezing, cryogenic burns, hypothermia	0.233	Hydrogen fuel cell
20	Electric shock activating the H/T system for timers start of charging or A/C	0.233	Battery electric
21	Gas or liquid leak in the hydrogen tank	0.206	Hydrogen fuel cell
22	Noise	0.145	General repairs
23	Electric shock caused by auxiliary battery disconnection in the process of loading	0.122	Battery electric
24	Airbags, risk of activation after disconnection from the A/T	0.119	Battery electric
25	Dermatitis	0.116	General repairs
26	Battery terminals, arc flash hazard in high humidity environments	0.100	Hydrogen fuel cell
27	Battery weight	0.070	Hybrid
28	Electric shock caused by damaged traction batteries	0.059	Battery electric
29	Vapors from battery	0.059	Hybrid
30	Overexertion	0.058	General repairs
31	Hydrogen fires (flames are transparent)	0.028	Hydrogen fuel cell
32	Electric shock caused by machine diagnostic connector (SAE J1962)	0.026	Battery electric
33	Electrolyte projections	0.023	Hybrid
34	Electric shock, beginning of repair process	0.019	Battery electric
35	Fall from height	0.018	General repairs
36	High concentrations of hydrogen and oxygen displacement, asphyxia	0.012	Hydrogen fuel cell
37	Liquid hydrogen tanks, air condensation on the valves	0.008	Hydrogen fuel cell
38	Splashing	0.007	General repairs
39	Airborne particles	0.006	General repairs
40	Damaged traction batteries, exposure to chemicals	0.005	Battery electric
41	Cutting	0.002	General repairs
42	Burning	0.002	General repairs
43	Electric shock	0.002	General repairs
44	Explosion, fire, toxic smoke	0.002	Hybrid
45	Damaged traction batteries, splashing at high temperatures	0.002	Battery electric
46	Fall at the same level	0.001	General repairs
47	Thermal stress	0.001	General repairs
48	Radiation	0.001	General repairs

4.2. Impact on the industry

The results and conclusions of this research can be used by automobile repair companies in various ways. More specifically, managers, safety supervisors, and mechanics can improve preventive measures for associated risks with specific activities studied and valorated by experts. Moreover, managers can estimate the exposure time for each mechanic, based on the work schedule, and thus calculate the total risk. This calculation can be made by considering the job profiles at the workplace and the tasks associated with them. Automobile repair companies can use the results of this study in their safety training programs and also to formulate occupational safety strategies.

Table 17
Comparison of technologies according activities scores.

Technologies	Activities		
	Number of activities evaluated	Total risk score	Average of risk per activity
General repairs	17	42.4	2.49
Hybrid	8	17.7	2.21
Battery electric	5	11.7	2.34
Hydrogen fuel cell	12	30.3	2.53

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