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The safe use of two-post above-ground automotive lifts (2PAG lifts) has received particular attention in the province of Québec (Canada) following the death of a young mechanic. The inspection and preventive maintenance of this equipment is a problem highlighted in accident investigation reports and by representatives of the sector. Therefore, the work presented in this article aimed at proposing a complete and detailed inspection grid for 2PAG lifts by establishing an exhaustive list of verification criteria, baseline states and the inspection frequency for each criterion according to their criticality. The grid was built from standards, existing grids, manufacturers' manuals, interviews and tests. The inspection frequency for each criterion was established using a decision-making algorithm, notably using the concepts of progressive and sudden failures as well as redundancy. Twenty-three of the 74 inspection criteria established in the grid require routine monitoring.

Keywords: occupational safety; automotive lift; vehicle falling off; inspection checklist; risk-based inspection

1 Introduction

1.1 Vehicles falling off two-post above ground automotive lifts

The two-post above ground automotive lifts (2PAG lifts) are used for the maintenance and repair of vehicles in automotive garages. This type of lift provides unobstructed access under the vehicle. As shown in Figure 1, a 2PAG lift consists of two columns anchored in concrete in which carriages are driven by a hydraulic cylinder. The two carriages are synchronized by a system of cables and pulleys (i.e., equalizer cables). Fall-arrest latches placed in each column allows the carriages to be mechanically supported and locked in place every 15 cm, instead of always relying on the hydraulic pressure in the cylinders. Each carriage supports two telescopic arms that can be locked in rotation by a locking device placed at the pivot. Finally, each arm is made up of two or three sections and is equipped with a height-adjustable support pad to make contact with the lifting points under the vehicle.

When using the 2PAG lift, mechanics work directly under or near a multi-ton elevated load, which is a hazardous work activity. In the United States~~, for example,~~ the Automotive Lift Institute (ALI) ALOIM standard is the safety reference document for the operation, inspection and maintenance of this type of equipment [1]. In the province of Québec (Canada), it is estimated that there were 30,000 automotive lifts in operation in 2019 (population: 8.4 million; ratio of 3.5 lifts per 1,000 inhabitants). 2PAG lifts are the most common type of lift in automotive garages due to ease of installation (completely above ground equipment), small footprint and versatility. In an online survey of businesses in the automotive service industry, 14% of garages (17 of 124 respondents) said that a vehicle installed on a lift had fallen off over the last 10 years but without anyone being injured [2]. These vehicle falls sometimes lead to a fatal accident.

Table 1 provides a description of two recent fatal accidents involving a vehicle falling off a 2PAG lift [3,4]. The causes stated in the investigation reports were both related to inadequate maintenance and deficient mechanic training. Thus, some of the causes identified for these two accidents could have been identified during periodic inspections (bolded in Table 1). This article focuses on the inspection of 2PAG lift.

Table 1. Description of two fatal accidents involving a vehicle falling off a 2PAG lift in the province of Québec (Canada) [3,4]

Year	2014	2018
Garage size	3 berries.	4 berries.
2PAG lift	Symmetrical. Capacity: 9000 lb (4100 kg). Year of manufacture: 2003.	Symmetrical, Capacity: 9000 lb (4100 kg). Year of manufacture: 1995.
Lift wear	Purchased used. No inspection log.	Purchased new. No inspection log.
Type of vehicle Loading	Honda Odyssey LX van (1940 kg). No loading in the trunk.	GMC Sierra 2500 pickup truck (2800 kg). No loading in the trunk.
Type of support pads Positioning Condition	Metal articulated support pads ("flip"). Placed at the recommended lifting points. **7 to 15° of inclination for the left front support pad**, 3 to 7° for the others.	Metal articulated support pads ("flip"). Positioning of support pads not known. No mention of the condition and play in the support pads.
Work activity	Lifting of the vehicle completed. In static phase. Visual inspection. No action on the vehicle.	Lifting of the vehicle completed. In static phase. Unscrew the bolt of the tank. Low applied forces.
Arms involved	Front left.	Rear, possibly right rear.
Position of the vehicle	Shifted to the right according to the length of the arms.	Advance and centering not known.
Fall-arrest latches	Use not determined. Functional devices.	Use not determined. Functional devices.
Stain	No mention of rust or grease product.	No mention of rust or grease product.
Locking of the arms	Locking engaged at the time of the accident. **Only two teeth in contact. Important play due to teeth wear and deformation**.	**Locking not systematically engaged. Engagement of the gear teeth difficult. Device at the back right not functional.**
Summary of stated causes	Support pad play, generate lateral forces. Large play in the arm locking devices. Integrity of the arm locking devices not satisfactory.	Unexpected opening of the rear lifting arms. Alteration of the arm locking devices Lack of training on the use of the lift.

Note: 2PAG= two-post above ground automotive; Bolded text in this table identifies causes that could have been identified during a periodic inspection.

1.2 2PAG lift Inspection

Periodic inspection of lifting equipment is a requirement in most occupational health and safety regulations (e.g., federal in the United States and Canada, province of Québec in Canada, France) [5-8]. The Canadian standard CSA B167 [9] on lifting equipment (e.g., lift, crane, etc.) prescribes an inspection frequency based on the service class of the equipment.

Periodic inspections can be defined as regular, planned inspections of critical equipment components to detect anomalies. They are initially visual, sound and generally do not involve disassembly. They are followed by equipment refurbishment if necessary [10]. According to a study by Megaw [5], the time available for the inspection and the feedback given to the inspector on his or her evaluations can impact the accuracy of visual inspections among other factors.

In the literature, the available automotive lift-specific documents are good practice guides and standards for design, maintenance, and use [1,12-16]. Relatively recent studies specific to 2PAG lifts focus on arm locking devices. Barnett and Glaubert [17] confirmed the importance of arm locking devices by modeling the structural behavior of 2PAG lifts under load. Woody and Mc Donald [18] identified an issue with the design of these locking devices. Most of the locking devices found on the UK market did not meet the requirements of BS EN 1493 [13] for minimum locking resistance (i.e., force equivalent to 4.5% of the lift capacity, applied perpendicular to the end of the arm fully extended in the horizontal plane; never less than 1500 N).

Regarding the periodic inspection of automotive lifts, some standards provide a checklist of items to be inspected [1,12,14]. Checklists are also available in technical guides and from specialized inspection companies [19,20]. Automotive lift instruction manuals are also a primary source of information [21,22]. Indeed, according to the ISO 12100 standard (safety of machinery) [23], a machine should be accompanied by an instruction manual that includes the nature and frequency of inspections for safety functions (s. 6.4.5.1).

During the periodic inspection, the items to be checked include the overall operation of the lift, the arm locking devices, the condition of the support pads, the fall-arrest latches and the equalizer cables. However, the check criteria proposed in the grids are mostly minimalist and subjective (e.g., "check arm play"; "check arm wear and sag"). For example, in the 2014 fatality (Table 1), was the play in the arm locking devices acceptable? The subjectivity of some of the criteria could be reduced by identifying precise baseline state. BS 7980 [14] offers an element of answer for lift arm play by stating that the play when the arms are fully extended should not exceed the diameter of the support pad (if circular) or the size of the smallest side of the support pad. This criterion has no scientific basis in the strict sense, but rather is based on common sense in relation to the operation of a 2PAG lift.

In the absence of a manufacturer's recommendation, an annual inspection is the minimum required by ANSI and ALI [1] or the regulations mentioned above. In the available inspection grids, the associated inspection frequency ranges from daily to annual. Thus, it is recognized that some inspection points require more frequent monitoring, particularly because of their criticality (e.g., arms, support pads). However, no detailed approach is available in the literature to justify these inspection frequencies, especially in the absence of manufacturer's recommendations.

1.3 Objective

The objective of the research was to develop a comprehensive and usable inspection grid for 2PAG lifts through two sub-objectives:

(1) Establish a comprehensive list of audit criteria and their baseline state (quantitative or qualitative)

(2) Establish the frequency of inspections for each criterion by the analysis of criticality (Risk Based Inspection, RBI).

The full range of safety considerations in the use of the 2PAG lifts was taken into account, including considerations that were not associated with the fall of vehicles (e.g., condition of the guards).

2 Methodology

2.1 General framework

This research is part of a more global project on the safe use of 2PAG lift. A multidisciplinary, engineering-ergonomics approach was used in order to take into account all the factors that can contribute to the fall of a vehicle from a 2PAG lift (Figure 2). The approach combined experimental designs to test the influence of some parameters (force distribution in the four arms [2]; support pad slippage at the lifting points [24] and analysis of the real work activity of mechanics in automotive garages.

2.2 Development of the inspection grid

The development of the inspection grid was done progressively from a detailed analysis and comparison of the data collected during the preparatory phase (e.g., available inspection grids, interviews with key players), experimental testing (e.g., inspection of the 2PGA lifts on which the tests were conducted) and field observations (e.g., inspection and measurements on the 2PAG lifts where mechanics were observed; complete analysis of the verbatim records) (Figure 2). Different data sources were therefore used (i.e., interviews, testing, documentation) to allow for triangulation of results and thus ensure robustness [25].

All inspection criteria, as well as the baseline states retained in the grid, were justified based on a specific reference from the following sources of information: standards [1,12,14], automotive lift instruction manuals [21,22,26], existing inspection grids and other unpublished documents [19,20,27-30] and verbatim records of interviews.

As the grid was developed, other inspection points, sub-points and inspection criteria were added until the analysis of the collected data was saturated.

The grid is divided into four levels:

(1) Inspection points: components of the lift to be inspected (e.g., arm locking devices).

(2) Inspection sub-points: aspect of the component that needs to be specifically inspected (e.g., operation of arm locking devices).

(3) Inspection criteria: definition of the measurement or assessment to establish the condition of a sub-inspection point (e.g., full mechanical engagement of the arm locking devices).

(4) State: quantitative or qualitative values that establish the condition of an inspection criterion (e.g., confirmed full engagement of the arm locking devices or partial engagement).

A first complete version of the grid was submitted for comments to prevention consultants from the sector's joint association (i.e., Auto Prevention). The grid was then tested in a professional training center by the research team, two prevention consultants and a teacher from the training center. The main purpose was to validate the relevance and formulation of the inspection criteria, as well as the adequacy of the state designation in practice. Some adjustments were made to the grid following this exercise (e.g., rewording of the instructions for establishing certain states).

2.3 Inspection frequency and criticality

The second step in the development of the grid was to establish the inspection frequency for each inspection criterion in order to increase the inspection frequency of criteria with high criticality and to reduce those of less critical criteria. The optimization of inspection frequencies based on failures is a broad topic that has long been addressed in the literature especially for complex systems [31,32]. For a simple piece of equipment such as the 2PAG lifts, a methodology based on Risk-Based Inspection (RBI) principles was used [33]. According to Selvik et al. [34], "the RBI is commonly used in planning of inspections for static mechanical equipment, in particular piping networks. The inspections are prioritized based on risk, expressed as expected values, integrating the likelihood and consequences of failures." The oil and process industries are particularly concerned with this approach and its optimization since maintenance planning is particularly complex and critical there [34-40]. Examples applied to the construction sector [41,42] and to elevators [43] are also available. RBI is usually subdivided in three categories: qualitative approach (which is based on engineering judgment), quantitative approach (which is based on probabilities and statistics), and semi-quantitative approach (which is a mix of qualitative and quantitative approaches) [43]. RBI often relies on engineering judgment and can be prone to human biases and errors [44]. In order to limit those errors, recent research has been focusing on the use of machine learning approach for RBI. The results are promising but machine learning should be complemented by human intelligence [45]. Dynamic Bayesian Networks are also used to optimize the inspection strategy for complex systems as a whole instead of focusing on individual system components [42].

Reducing costs while maintaining an acceptable level of risk is the basis for optimization research in methodologies associated with RBI [46]. RBI aims to rationalize the inspections by determining: where to inspect, what to inspect, how to inspect and when to inspect [46]. Fuzzy logic has been used to optimize the convergence of results when estimating the severity and frequency of damage occurrence [37,38]. The Analytical Hierarchy Process (AHP) has also been used in conjunction with RBI to select the most appropriate maintenance strategy based on the level of risk assigned to the equipment [39].

Methodologies associated with RBI often use a risk matrix (severity x probability, i.e. quantitative approach) to estimate the risk level and then the priority and frequency of inspection. In our highly focused case study, prioritization is assessed solely by the probability of failure since the targeted damage is unique as is the type of equipment (i.e., serious injury or death from vehicle falling off the lift). In this study, a qualitative approach was used due to the lack of technical data available. A decision algorithm, rather than a probability scale, was thus used to characterize the targeted failures. The concepts associated with the failures that emerged as important were whether the failure (1) may contribute to the vehicle falling off the lift, (2) is sudden or progressive, and (3) is associated with other measures to prevent the fall. A progressive failure (as opposed to a sudden failure) is a "failure that could have been predicted by examination or monitoring" [47]. A progressive failure that is not monitored over time and is never detected can eventually lead to complete failure of the equipment. For example, some horizontal play in the arms of the 2PAG lift is normal even when the lift is brand new. However, this play can increase with wear and tear and cause the support pad to move enough to leave its support under the vehicle. Monitoring over time is therefore required to compare the measured play with the initial or previous one and thus detect the onset of this progressive failure before it reaches a critical level.

Based on the developed, tested and finalized inspection grid, an analysis of each criterion was performed using the decision algorithm in Figure 4. The final result was reached by consensus after a few iterations.

3 Results

3.1 Inspection grid

The inspection grid developed for the 2PAG lift is available in the supplementary materials. It is essentially aimed at safe operation of the 2PAG lift and is intended for qualified personnel. An overview of the structure is available in Figure 3.

Table 2 summarizes the content of the grid, which includes 15 inspection points divided into 6 categories (numbered A to F).

Table 2. Quantitative overview of the developed inspection grid

Categories	**Inspection points**	**Sub-points**	**Criteria**				
			Total	**With follow -up**	**Full inspection**	**Periodic inspection**	**Routine inspection**
A. General	A.1 Documents and safety instructions	4	4	0	4	0	0
	A.2 General Safety	3	3	0	3	0	0
B. Structure	B.1 Fixing elements of the columns	3	6	4	0	2	4
	B.2 Columns	2	3	3	0	3	0
	B.3 Lifting carriages	3	4	2	0	2	2
C. Lifting arm	C.1 Arm locking devices	2	3	1	0	0	3
	C.2 Arms	4	10	7	1	4	5
	C.3 Support pads	3	5	3	0	1	4
D. Functional tests without load	D.1 Unloaded lifting	4	9	1	4	3	2
	D.2 Unloaded lowering	3	8	0	6	1	1
E. Electromechanical components	E.1 Hydraulic system	3	3	1	1	2	0
	E.2 Equalizer device	2	5	1	0	5	0
	E.3 Electrical system	2	3	0	3	0	0
F. Functional tests with load	F.1 Loaded lifting	3	6	0	1	4	1
	F.2 Loaded lowering	1	2	0	1	0	1
Total	15	42	74	23	24	27	23

The grid has seven columns including the four levels described in Section 2.2 (i.e., inspection point/sub-points, inspection criteria, state). Explanations of the procedure for establishing the state, if necessary and the need for follow-up over time for progressive failure are provided (e.g., how to evaluate the resistance of arm locking devices; photography to document the condition and compare its evolution). These last two columns were developed mainly through criteria from the literature and testing of existing grids in real life situations with easily accessible tools such as a spirit level, tape measure, inclinometer and laser pointer. Finally, a supporting reference and the inspection periodicity (section 3.2) constitute the last two columns of the grid.

3.2 Inspection frequency

3.2.1 Decision-making algorithm

In order to establish the criticality of a criterion according to the parameters mentioned in Section 2.3, the decision algorithm consists of four questions (Figure 4).

1. Can the failure covered by the inspection criterion contribute to a vehicle falling off the lift? This first question makes it clear that periodic or routine lift inspections are primarily intended to reduce the risks associated with a vehicle falling off the lift. For example, an inspection criterion regarding work area clearance does not affect the risk of a vehicle falling off, but it may identify a safety issue to mechanics. **2. Is the failure covered by the inspection criterion normally sudden or progressive?** This question establishes that inspection criteria associated with sudden failures generally require a higher inspection frequency since it is not possible to track their progress. For example, an inspection criterion for degradation (e.g., rust) of column anchor nuts in concrete will be considered a progressive failure, whereas a criterion for lack of contact between the anchor nuts and the column attachment plate will be classified as sudden failure. **3. Can the progressive failure addressed by the inspection criterion result in the complete loss of the required function?** This question identifies inspection criteria associated with progressive failures that could suddenly result in loss of function. These criteria normally require a higher inspection frequency. For example, the inspection criterion for the level of degradation (e.g., wear) of the mechanical components of the arm locking devices will be considered a progressive failure, but which may over time lead to sudden loss of the locking function. **4. Are other measures in place (redundancy, complementary measures, other functional inspection criteria, etc.) to prevent the vehicle from falling as a result of the failure covered by the inspection criterion?** This question allows for a reduction in the frequency of inspection for certain criteria where redundancy is in place to reduce the likelihood of a vehicle falling off the lift. For example, the criterion for the level of degradation of the fall-arrest latches (see Figure 1) refers to the (progressive) failure of this safety device. However, complete failure of the fall-arrest system does not necessarily result in the vehicle falling off the lift: the hydraulic system is still there to keep the vehicle up.

3.2.2 Application of the algorithm

The algorithm allows the inspection criteria to be divided into three inspection frequencies: full inspection (F) (e.g., annual), periodic inspection (P) (e.g., monthly), and routine inspection (R) (e.g., weekly). Although it is up to each user to determine the frequency of their inspections, annual, monthly and weekly frequencies are provided as examples to better illustrate the concept of the three levels of inspection. Depending on the type of lift and its use (sporadic or continuous use, mostly light vehicles or heavy vehicles close to the maximum rated weight, work environment that limits/accelerate corrosion), the user of the automotive lift shall determine the frequencies for the full inspection, periodic inspection and routine inspection. As a reference, the US ANSI/ALIOM standard [1] states "inspections shall follow the recommendations of the lift manufacturer as to frequency". Without regard to the frequency of inspection specified by the lift manufacturer, the standard states that lifts shall be inspected annually by a qualified lift inspector. Moreover, the UK BS 7980 standard [13] recommends: daily inspections (e.g. steel wire ropes, locking mechanism), monthly inspections/maintenance (e.g. lubrication, anchor bolt verification), and a six monthly "thorough examination" conducted by a competent person.

The results of the application of the algorithm on the 74 criteria are available in the grid in the supplementary materials and in the compilation in Table 2. All 23 of the routine inspection criteria apply to failures that may contribute to a vehicle falling off and for which there is no other measure in place to prevent the vehicle from falling. An example of this is the criterion on the surface condition of support pads (criterion C.3.2) since it is the interface between the lift and the vehicle. The periodic inspection adds 27 specific criteria to those of the routine inspection. In accordance with the decision algorithm, six of these criteria fall into the category of sudden failures where other measures are in place to prevent the vehicle from falling off. The anchor nut torque criterion (criterion B.1.3) falls into this category since the failure may be sudden (e.g., anchor bolt may suddenly fail when the torque wrench is used), but there are multiple bolts holding the columns (redundancy). Fifteen of these 23 criteria fall into the category of progressive failures that may not result in complete loss of the required function, such as the criteria for column verticality (criterion B.2.2).

Finally, the comprehensive inspection adds 24 criteria to the periodic and routine inspection criteria. These criteria address deficiencies that may not result in a fall of the vehicle, but may present another risk to the mechanic. For example, there are criteria regarding the presence and legibility of manufacturer's safety instructions and pictograms near the control station (A.1.4), and clearance of the work area and workstation (A.2.1 and A.2.2).

3.2.3 Discussion of criticality and measures for state determination by category

Criteria for category "A. General"

The "General" category includes inspection sub-points and criteria that relate to the documentation, safety procedures, and general safety of the 2PAG lift. The seven criteria in this category are part of a full inspection.

Criteria for category "B. Structure"

This category concerns the fastening elements of the two columns of the lifts (B.1), the columns themselves (B.2), as well as the lifting carriages which are the mobile elements connecting the lifting arms to the columns (B.3). Of the thirteen criteria in this category, nine require monitoring over time and six are part of routine inspections. This is expected since many of the structural elements of lifts are subject to progressive failures that can contribute to a vehicle falling off the lift.

Important inspection criteria for column anchorage include the concrete around the anchors (B.1.1). A criterion was proposed based on information from the inspection grid of one 2PAG lift manufacturer [27], which emphasizes that signs of floor fatigue (such as cracks) should not be found within 15 cm (6 in.) of the anchor plates (Figure 5a). A follow-up with a photo by placing a tape measure as a marker is recommended. In this section of the grid, there are also criteria for contact between the anchor plate and the floor and between the anchor nuts and the anchor plate (under B.1.2 and B.1.3). These criteria were considered as potential indications of looseness of the column fasteners. Similarly, a criterion for anchor nut torque was found in several references [27]. In this case, a torque wrench measurement should be performed to confirm that the torque is within the manufacturer's recommended values. The use of the torque wrench could potentially reveal concrete degradation at the anchor points, e.g. as a result of the combined effect of water and de-icing salts used during winter season (Figure 5b).

For columns, in addition to their general condition (B.2.1), the inspection criteria also focus on their verticality (B.2.2), a potential sign of anchor failure. These criteria are monitored over time and measured with a spirit level.

Some significant inspection criteria for automotive lifts concern the arm pivots (B.3.2). Indeed, these components are the only means of attachment of the lifting arms.

According to what has been collected in the different references, the inspection will focus on their possible deformation or the presence of corrosion, the welds of the parts that compose them as well as the presence of the axis pin or retaining elements of the pivot. These criteria are part of the routine inspection.

Criteria for category "C. Lifting arms"

The inspection items included in this category are the arm locking devices (C.1), the arms themselves (C.2), including extensions, and the support pads (C.3). Of the 18 inspection criteria in this category, 11 require follow-up over time and 12 are routine inspections. Lift arm components are often critical to the risk of a vehicle falling off.

Two of the most important inspection criteria are the mechanical engagement and resistance of the arm locking devices (under C.1.2). A failure of this device can significantly increase the risk of a vehicle falling off. The ANSI and ALI [29] and AFNOR [12] standards specify values for the resistance of the arm locking devices (e.g., 667 N at the end of the extended arm for the ANSI and ALI standard [29]). However, it is difficult to validate these values in the field without a dedicated measuring instrument. The objective of the study is to propose an inspection grid accessible to users of 2PAG lifts in the field. A simple test is therefore proposed: a vigorous push with the foot at three points along the rotation path of each arm. This approach, coupled with a visual inspection of the condition of the locking devices, verifies that they are functional and that their resistance is significant. A similar approach is proposed for the arm extension stops (under C.2.2), another critical factor.

The sub-point "position and movements of the arms" (C.2.4) includes several criteria to determine the level of arm wear (e.g., play, vertical offset between two arms) that may result in an inclination of the lifted vehicle. Too much inclination of a vehicle can change the vertical forces at the support pads or potentially causing a slip off of the vehicle from the support pad [2]. Measurement of arm inclination can be done using an inclinometer or spirit level. Measurement of arm play can also be done simply with a ruler on the ground and a laser pointer placed at the end of the extended arm (Figure 6). As mentioned in Section 1.2, this value should be less than the smallest dimension of the support pad [14].

The support pad inspection criteria (C.3) are primarily concerned with the attachment/adjustment devices and the support pad surface. The criterion "maximum angular play of the support pads" (under C.3.3) measured with an inclinometer allows to verify if the support pad adjustment devices are worn to the point where the support pads could be too inclined to adequately support the vehicle (a follow-up over time is necessary to identify a significant increase of the angular play compared to the new condition). As discussed earlier, the inclination at the support pads results in horizontal forces that tend to pull the arm in and to rotate the arm out. These factors influence the stability of the vehicle on the lift.

Criteria for category "D. Functional tests without load"

In this category, the lift is subjected to functional tests without load (i.e., lifting and lowering) that allow for a more thorough inspection. In particular, inspection criteria are proposed to evaluate the proper operation of the controls (D.1.1, D.2.1 and D.2.2) and the smoothness of the lift movements (D.1.2 and D.2.3). Of the 17 inspection criteria in this category, only one requires follow-up over time and only three are part of routine inspections.

Several criteria concern the sub-point "fall-arrest latch" (D.1.3). The engagement and synchronization of the latches are particularly targeted. Too much misalignment in the engagement of the latches of the two columns can lead to a dangerous situation. If only one of the two latches is engaged when the mechanic lowers the vehicle to rest on the latches, this can lead to an unintended inclination of the vehicle. This situation can dangerously affect the load distribution in the arms and the stability of the vehicle. The check in this case is primarily auditory according to the inspector's experience.

Criteria for category "E. Electromechanical components, power transmission"

This category includes the hydraulic system (E.1), equalizer device (E.2) and electrical system (E.3) and has 11 inspection criteria. These criteria are part of the periodic or complete inspection.

Hydraulic system inspection criteria are primarily geared toward finding actual or potential leaks. A leak in a component of the hydraulic system can be a precursor to a possible complete failure of the component, which could cause a jerk during the lifting, or a rapid lowering of a vehicle. This is why most of the references consulted mention it.

The equalizer device of a 2PAG lift allow to synchronize the lifting or lowering of the two carriages in order to keep the vehicle horizontal. It is normally composed of cables or chains (E.2.1) and pulleys or sprockets (E.2.2) allowing the transmission of the movement from one side of the lift to the other. Failure of this device could cause the vehicle to move up or down faster on one side than the other, affecting the vehicle stability. A test for cable tension is included in the grid (i.e., pull the cables together with two fingers without much effort).

The electrical system components of a 2PAG lift do not have an impact on the risk of a vehicle falling off. However, there are inspection criteria related to general safety, such as the condition of the electrical wiring (E.3.1).

Criteria for category "F. Functional tests under load"

Most of the eight inspection criteria in this category are a repetition of those for the no-load tests. However, additional criteria have been provided to observe the arms and columns under load (F.2). The criteria of arm and column deformation (periodic inspection) and differential inclination between the two left and right arms (routine inspection) were added to visually validate the effect of a loading based on user experience. None of the criteria in this category require monitoring over time.

4 Conclusion

An inspection grid specific to the 2PAG lifts, as exhaustive as possible, was developed and each inspection criterion was associated with an inspection frequency through a criticality-based decision algorithm. The concepts of progressive or sudden failures as well as redundancy were used to establish the criticality and the inspection frequency. Each criterion in the grid is justified with a reference. Measures were suggested to determine certain state to ensure qualitative or quantitative follow-up over time and to make the inspection results less subjective. With the follow-up notations, this grid can be used as a post-installation inspection of a lift and thus serve as a reference for subsequent periodic inspections. One limitation of this study is the lack of available data to determine the inspection frequencies (e.g. annual, monthly, weekly). Each user of 2PAG lift will have to assess the frequencies of the full inspection, periodic inspection and routine inspection based on its use case scenario and the local occupational health and safety laws and regulations.

The inspection grid developed is essentially aimed at ensuring safety during the use of the 2PAG lift. It is not necessarily exhaustive with regard to reliability and maintenance aspects that do not have an impact on safety. Beyond the inspection, a 2PAG lift must be regularly maintained in accordance with the maintenance manual provided by the manufacturer (e.g., lubrication, greasing, change of wearing parts, cleaning). Moreover, the criteria listed in this inspection grid should be considered in the absence of more specific guidelines from the manufacturer.

Finally, the principles used in the decision-making algorithm to optimize the inspection frequency of the different criteria could easily be used for the inspection of other types of lifting equipment (e.g., jib cranes, overhead cranes). This is an avenue of prevention to be explored.

5 Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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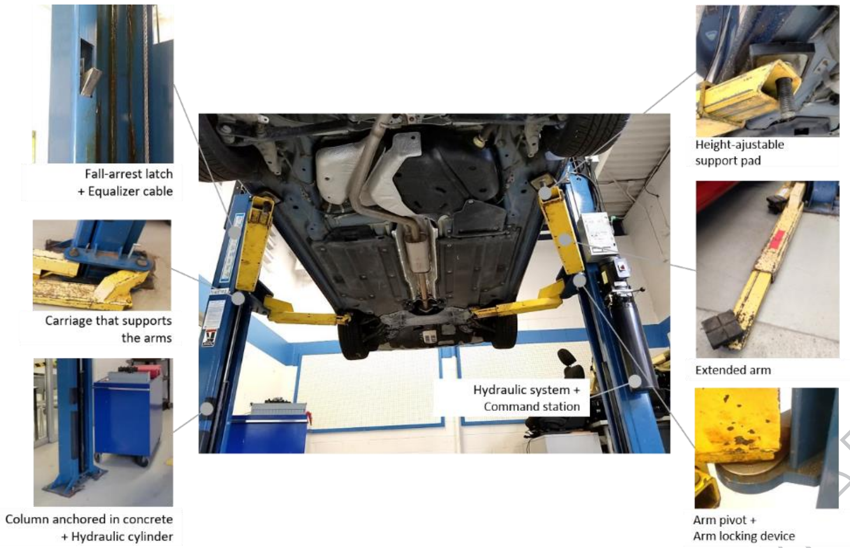
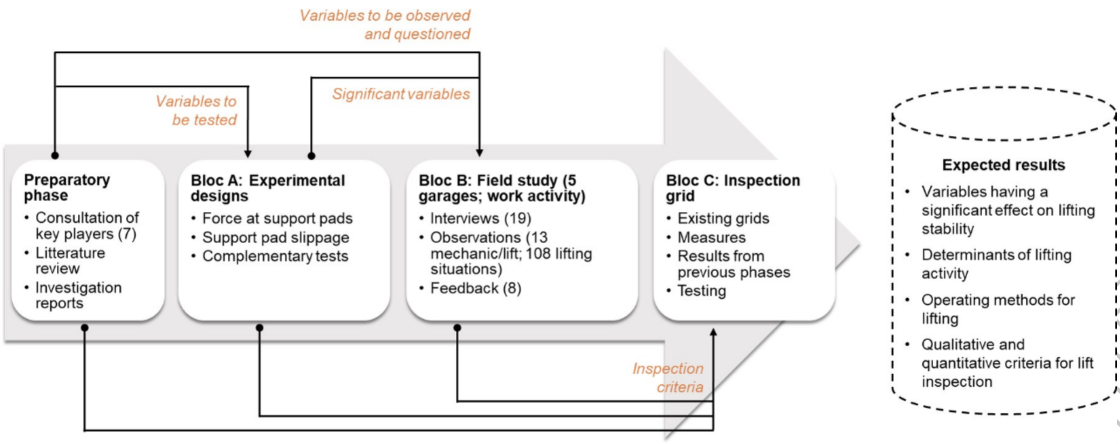
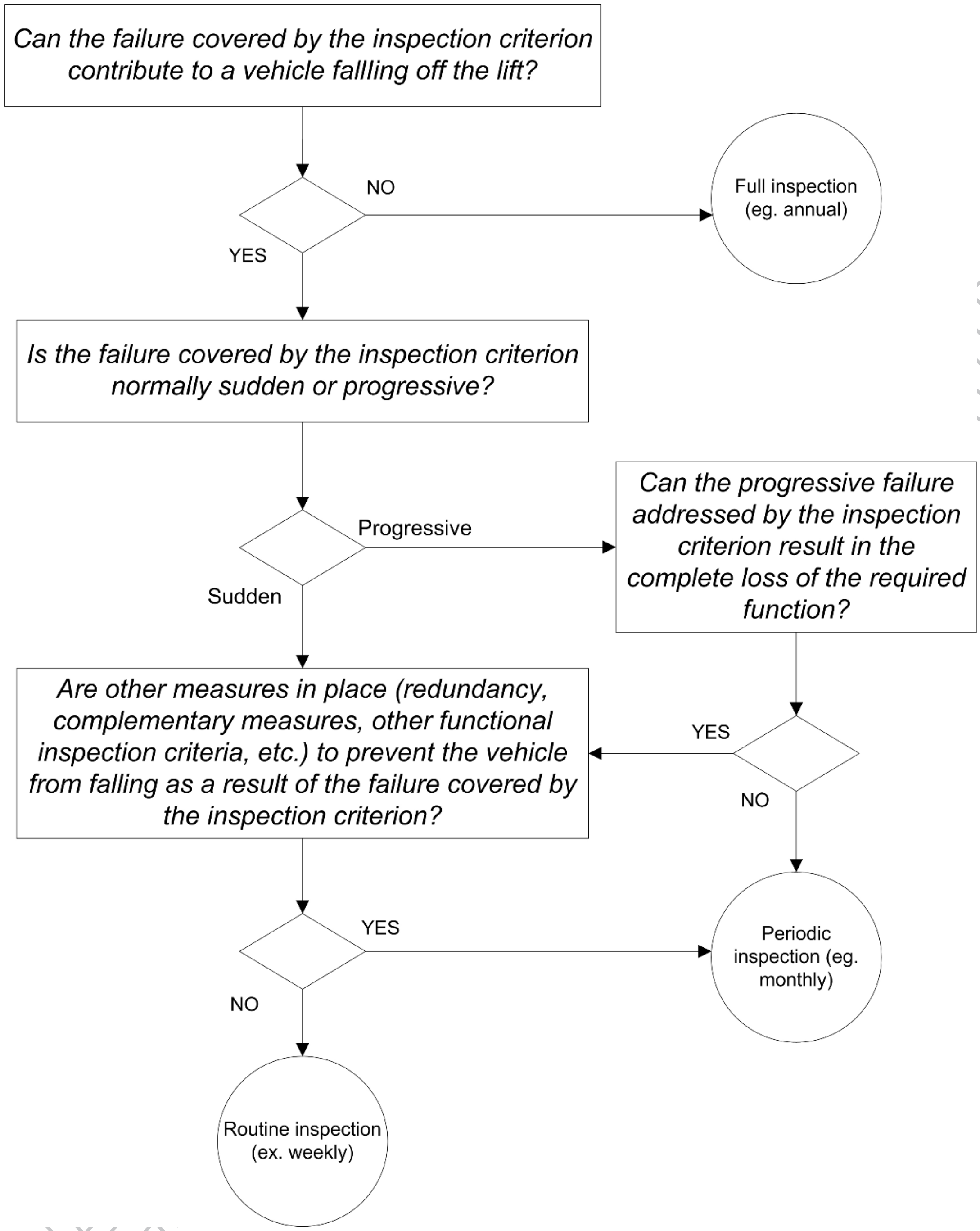

Fall-arrest latch
+ Equalizer cable
Carriage that supports
the arms
Column anchored in concrete
+ Hydraulic cylinder
Height-ajustable
support pad
Extended arm
Hydraulic system +
Command station
Arm pivot +
Arm locking device


Variables to be observed and questioned
Variables to be tested
Significant variables
Preparatory phase
• Consultation of key players (7)
• Litterature review
• Investigation reports
Bloc A: Experimental designs
• Force at support pads
• Support pad slippage
• Complementary tests
Bloc B: Field study (5 garages; work activity)
• Interviews (19)
• Observations (13 mechanic/lift; 108 lifting situations)
• Feedback (8)
Bloc C: Inspection grid
• Existing grids
• Measures
• Results from previous phases
• Testing
Inspection criteria
Expected results
• Variables having a significant effect on lifting stability
• Determinants of lifting activity
• Operating methods for lifting
• Qualitative and quantitative criteria for lift inspection

Inspection Points/ sub-points	Inspection criteria	State	Explanations	Follow-up	Justification (examples of references) Quebec Laws and Regulations; Standards; Manufacturer's manual; CFPA tests; Verbatim records; Other (e.g., inspection grids)	Periodicity
B. Structure						
B.1 Fixing elements of the columns (inspect both columns)						
B.1.1 Concrete around anchors	Presence of cracks or spalling at anchor points requiring follow-up	No signs of floor deterioration within 15 cm of the column (significant or deep crack, swelling, deformation requiring follow-up) Signs of deterioration within 15 cm (significant or deep crack, swelling, deformation requiring follow-up)	Photos with ruler next to them	X	**Manuals:** Visual compliance of the floor: visually ensure that the anchors are more than 6° away from any sign of floor fatigue (cracks, swelling, deformation, etc.). (Girolift, n.d.) **Verbatim records:** Anchoring at a distance of more than 15 cm (6 in.) from a crack or problem in the floor. Record of the condition of the floor. (Key players - Interview 4)	R


Can the failure covered by the inspection criterion contribute to a vehicle fallling off the lift?
NO
YES
Full inspection (eg. annual)
Is the failure covered by the inspection criterion normally sudden or progressive?
Progressive
Sudden
Can the progressive failure addressed by the inspection criterion result in the complete loss of the required function?
Are other measures in place (redundancy, complementary measures, other functional inspection criteria, etc.) to prevent the vehicle from falling as a result of the failure covered by the inspection criterion?
YES
NO
YES
NO
Periodic inspection (eg. monthly)
Routine inspection (ex. weekly)