Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 131 **2026**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2026.131.5

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Krajňák, J., Tomašková, M. Engine compartments of passenger cars: main sources of fire risk and modern prevention strategies. *Scientific Journal of Silesian University of Technology. Series Transport*. 2026, **131**, 89-101. ISSN: 0209-3324.
DOI: https://doi.org/10.20858/sjsutst.2026.131.5

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ENGINE COMPARTMENTS OF PASSENGER CARS: MAIN SOURCES OF FIRE RISK AND MODERN PREVENTION STRATEGIES

Summary. Motor vehicles constitute a key component of transport infrastructure and play an indispensable role in the movement of goods and the provision of services within logistics and distribution systems. Their reliable and safe operation is therefore essential not only from an economic perspective but also from a safety standpoint. The engine compartment represents one of the most critical zones in terms of fire safety. The elevated risk of fire initiation is determined by multiple technical and operational factors. Among the most significant are electrical failures, particularly short-circuit phenomena within the vehicle's electrical system, as well as the gradual degradation and wear of internal combustion engine components. An important role is also played by high operating temperatures and the presence of hot surfaces, which can act as ignition sources for flammable substances. The risk is further exacerbated by the reduced thermal and mechanical resistance of certain construction materials, especially polymer-based components, which are increasingly used in modern vehicles. Heat accumulation and restricted natural heat dissipation occur due to the structural enclosure of the engine compartment. At the same time, operating fluids (e.g., engine oil, fuel, coolant) and contaminants tend

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to accumulate in this space, representing a potential source of combustible material and contributing to the initiation and dynamic development of fire.
Keywords: fire, risk, prevention, transport vehicle

1. INTRODUCTION

The automotive industry has played a leading role in global economic development as well as in the advancement of new technologies [2]. The use of vehicles to achieve rapid and safe transportation to distant destinations represents a key factor contributing to national economic growth and the efficiency of logistics and service systems [3].

The engine compartments of passenger vehicles represent one of the most critical areas in terms of fire initiation, due to several factors, including electrical short circuits, engine wear and degradation, high temperatures of hot surfaces, reduced resistance of materials, extensive use of polymer components, engine compartment enclosure, and the accumulation of operating fluids and contaminants. Statistical data indicate that a significant proportion of vehicle fires originate in the engine compartment. For this reason, fire protection of engine compartments is a crucial aspect of overall vehicle safety.

Particularly challenging and severe are fires involving large vehicles. In such cases, the importance of careful and proactive planning of response resources is emphasized, as these incidents often require substantial towing capacity and extended intervention times, which consequently prolong incident clearance durations [1]. It is also essential to prevent vehicle fires in confined environments such as tunnels and enclosed spaces, where fire development can have significantly more severe consequences.

Research results indicate that both internal combustion engine vehicles and electric vehicles exhibit similar fire dynamics. Studies suggest that electric vehicles can produce a comparable heat release rate to vehicles powered by fossil fuels, although differences have been observed in smoke dispersion and visibility conditions [3]. During vehicle fires, special attention must be given to batteries. Lithium-ion batteries are frequently associated with fire incidents due to the phenomenon of "thermal runaway," which may occur during operation as a result of internal manufacturing defects or operational issues [4]. Conventional lead-acid batteries also present certain disadvantages and risks [5].

Several studies systematically address experimental research on passenger vehicle fires, particularly in the context of parking facility safety design [6]. A growing body of experts in fire safety engineering focuses on issues such as parking garage fire safety [7], protective measures and suppression systems [8,9], and effective smoke control strategies [7]. At the same time, there is an increasing need for high-quality, comprehensive data sources related to vehicle fire incidents.

This article provides a systematic analysis of the main risk factors, identifies critical ignition points, and proposes modern preventive measures that can significantly reduce the risk of fire occurrence and enhance the operational safety of passenger vehicles.

2. RISK PLACES FROM THE ASPECT OF FIRE

Engine compartments (e.g., in passenger cars and trucks) are among the riskiest places in terms of fire, because several initiating and supporting factors are concentrated here at the same time.

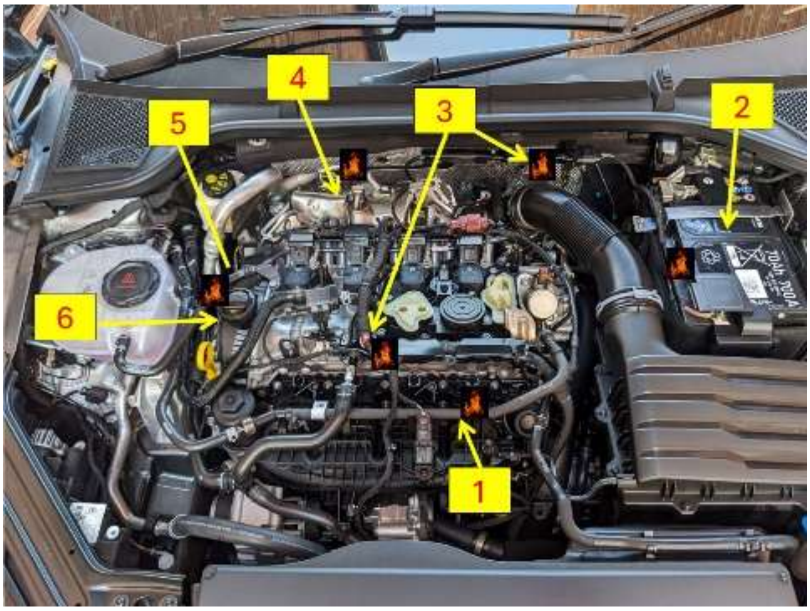

Fig. 1. Engine compartment of a Skoda Octavia passenger car with marking of fire risk points (1 - fuel pipe, 2 - battery, 3 - electrical wiring, 4 - catalyst (turbo), 5 - exhaust pipe, 6 - engine oil filler cap)

Figure 1 shows the engine of a Skoda Octavia passenger car with the plastic covers removed. The important engine compartments of the passenger car are marked there along with the identification of the main fire risk areas. The image presents the engine compartment after the covers have been removed, which allows for a more detailed localization of critical components from the point of view of fire initiation.

Position 1 represents the fuel line. From a fire safety perspective, this system is highly hazardous, as leakage failures or mechanical damage may lead to fuel leakage (gasoline or diesel). In combination with the presence of ignition sources (e.g., hot surfaces or sparks), there is a high risk of fire initiation.

Position 2 shows the battery (accumulator), which represents a significant source of electrical hazard. Short circuits, overheating, conductor burnout, or sparking may occur, potentially leading to fire initiation, especially in cases of insufficient insulation or mechanical damage.

Position 3 indicates the vehicle's electrical wiring. The electrical system is prone to insulation degradation, mechanical damage, or loose connections, which may result in sparking or short circuits. These phenomena represent significant ignition mechanisms for fire development in the engine compartment.

Position 4 identifies components with high surface temperatures, such as the catalytic converter or turbocharger. These parts reach extreme temperatures during operation and may cause ignition of flammable liquids (e.g., leaking oil or fuel) upon contact.

Position 5 refers to the exhaust system, located in the lower part of the engine compartment. The exhaust system is characterized by high exhaust gas and surface temperatures, making it a potential ignition source for accumulated flammable substances or contaminants.

Position 6 represents the internal combustion engine itself, specifically the area of the engine oil filler cap. Leakage of engine oil, its degradation, or engine overheating may lead to the formation of a flammable environment [11]. Oil, in combination with high temperatures, poses a significant risk for both fire initiation and propagation.

The above-mentioned components represent the most critical areas from the perspective of fire safety in the engine compartment. Their technical condition, regular maintenance, and timely diagnostics are essential for minimizing the risk of fire occurrence in passenger vehicles.

Critical source of fire initiation within the engine compartment is represented by electrical faults, particularly short-circuit phenomena. These may arise due to thermal degradation or mechanical damage of electrical conductors, as illustrated in Figure 2. Damaged insulation or conductor exposure can lead to unintended current flow and localized overheating.

Additionally, as shown in Figure 3, the oxidation and corrosion of electrical contacts and connectors can significantly increase contact resistance. This condition may result in localized thermal loading, electrical arcing, or intermittent sparking. Such processes represent a significant ignition mechanism and may act as a primary trigger for fire initiation within the vehicle's electrical system.

Fig. 2. Damaged - burnt electrical insulation

Fig. 3. Oxidized electrical connections

The most common causes of fires due to electrical wiring are:
• damaged wire insulation,
• vibrations causing loose connections,
• corrosion of contacts,
• aftermarket devices (audio, lights).

The occurrence of a fire in the engine compartment may also be caused by various mechanical failures. Among the most common mechanical faults that may act as initiating factors of a fire are the following:
• engine oil leak,
• damaged fuel hoses,
• engine overheating,
• friction of moving parts.

Figure 4 illustrates damage to the drive belt (e.g., rupture or excessive wear) [13]. Such a failure may lead to secondary effects, including the formation of an electrical arc, localized overheating of components, or increased friction. As a result, fire initiation may occur, particularly in the presence of flammable materials such as plastic components or operating fluids.

Figure 5 shows engine overheating. The mechanism of fire initiation in this case is based on the contact of a flammable liquid (e.g., engine oil or fuel) with high-temperature surfaces. This contact may lead to ignition and the subsequent development of a fire within the engine compartment.

Fig. 4. Broken drive belt

Fig. 5. Overheating of a hot engine resulting in ignition of flammable liquids

From a fire safety perspective, hot surfaces of various engine compartment components represent a significant risk factor. These include parts such as the turbocharger, catalytic converter, and exhaust system, whose surface temperatures may reach approximately 300 to 800°C depending on operating conditions [10].

These components act as potential ignition sources, particularly in the event of contact with flammable liquids (e.g., engine oil, fuel, or other operating fluids). The impingement or leakage of such liquids onto heated surfaces can lead to rapid evaporation, formation of flammable vapors, and subsequent ignition. This mechanism represents a significant risk factor for fire initiation within the engine compartment of a vehicle.

The use of plastic materials in modern automobiles is essential and represents an integral part of contemporary vehicle design. Polymeric materials are widely used for protective covers, thermal insulation components, fuel system elements, and various structural parts within the engine compartment.

From a fire safety perspective, however, their application represents a significant risk factor. Operating temperatures within the engine compartment may, under certain conditions, exceed the ignition temperatures of some types of plastics. When exposed to elevated thermal loads or in contact with hot surfaces, these materials may undergo degradation, melting, and subsequent ignition, thereby creating a potential source of fire initiation.

Modern vehicles contain a high proportion of polymeric materials [12], which, in the event of fire, contributes to faster fire spread and increased fire intensity. Figure 6 illustrates the extensive use of plastic components in the engine compartments of Škoda Fabia and Figure 7 Mercedes-Benz vehicles, clearly demonstrating that these materials constitute a substantial part of the construction.

For this reason, from a fire prevention standpoint, it is advisable to prioritize the use of materials with higher thermal resistance, as well as non-combustible or self-extinguishing polymers, which can significantly reduce the risk of fire initiation and propagation within the engine compartment.

Fig. 6. Plastics in the engine compartment of a Skoda Fabia passenger car

Fig. 7. Plastics in the engine compartment of a Mercedes-Benz passenger car

Another significant factor affecting the fire safety of the engine compartment is its structural covering. Although enclosing the engine compartment brings certain advantages in terms of aerodynamics, optimization of air flow and noise reduction, it also presents several negative aspects. The main disadvantages include limited ventilation of the engine compartment, which leads to heat accumulation and increased thermal load on individual components. At the same time, vapors of flammable liquids (e.g., fuel or oil) accumulate, creating a potentially explosive or highly flammable environment. In the event of a fire, a sudden supply of oxygen may occur after opening the hood, which will cause intensive development of combustion (the so-called flashover effect), and thus a sharp deterioration in the course of the fire in the engine compartment. In Figure 8 we see an example of such an engine cover.

Another significant risk factor in terms of engine compartment fire safety is the accumulation of operating fluids and dirt. During vehicle operation, oil deposits, fuel residues, dust particles, and lubricant deposits are formed, which are deposited on the surfaces of individual components, as shown in Figure 9. These contaminants represent a potentially flammable material that can, under increased thermal load or contact with hot surfaces (e.g., exhaust pipe, turbocharger), undergo thermal decomposition, evaporation and subsequent ignition. The accumulation of these substances significantly increases the risk of fire initiation, especially in conditions of engine overheating or insufficient vehicle maintenance.

Fig. 8. Engine cover

Fig. 9. Dirty parts and oil residue on the engine

2.1. Calculation of fire in the engine compartment

The fire risk R is often expressed by the formula:

$$R = P \times C \tag{1}$$

P – probability of fire,
C – consequences of fire (damage, danger to people, technical loss).

For the engine compartment, this formula is extended by specific factors:

$$R = f(P_{\text{fuel}}, P_{\text{heat}}, P_{\text{electricity}}, C_{\text{damage}}) \quad (2)$$

Factors affecting the probability of fire (P). Before performing the fire calculation in the engine compartment, it is necessary to design Table 1, Evaluation of the engine compartment inspection. This table presents the value of the factor.

1. Fuel system
Fuel leakage (petrol, diesel)
Hose tightness, fuel pressure
Rating: 1 (low risk) - 5 (high risk)

2. Electrical installation
Condition of cables, insulation
Connections and short circuits
Rating: 1-5

3. Engine temperature and operation
Operating temperature (engine block, exhaust)
Oil and grease accumulation
Rating: 1-5

4. Maintenance
Frequency of cleaning and inspection engine compartment
Rating: 1-5

Tab. 1
Engine compartment inspection evaluation

Factor	**Value 1–5**
Fuel leak	3
Electrical installation	2
Engine temperature	4
Maintenance	2

The probability of a fire occurring is often calculated as a weighted average:

$$P = \frac{\sum(factor \times weight)}{\sum weight} \quad (3)$$

If all factors are equally important (weight = 1):

$$P = \frac{3+2+4+2}{4} = 2.75 \quad (4)$$

Calculation of total risk:

$$R = P \times C = 2.75 \times 3 = 8.25 \quad (5)$$

- Risk 1-5 → low,
- Risk 5-10 → medium,
- Risk >10 → high.

In our case R=8.25→ medium risk.

Table 2 shows the identification of fire initiation sources for individual components located in the front of the engine.

Tab. 2

Identification of fire initiation sources

Component	Risk Type	Probability (P)	Consequence (C)	Risk R = P×C	Note
Fuel Hoses & Injection	Combustible Leak	4	4	16	Critical element
Alternator + Wiring Short	Circuit / Sparking	3	3	9	Common cause
Battery	Short Circuit / Overheating	3	4	12	Damage risk
Exhaust Pipe / Turbo	High Temperature	4	3	12	Oil contact
Engine Oil Leak	Flammable Film	3	3	9	Secondary risk
Control Unit (ECU)	Electrical Failure	2	3	6	Low frequency

Calculation of the overall risk index:
Average probability:

$$P_{avg} = \frac{4+3+3+4+3+2}{6} = 3.17 \quad (6)$$

Average consequence:

$$C_{avg} = \frac{4+3+4+3+3+3}{6} = 3.33 \quad (7)$$

Overall risk:

$$R = 3.17 \times 3.33 = 10.56 \quad (8)$$

Engine compartment = Increased risk (10.56).
Most critical element: fuel system (R=16).

3. RISKINESS OF ENGINE COMPARTMENT COMPONENTS

Based on the risk assessment of individual components, it is possible to construct a risk distribution graph of engine compartment components. This approach enables a comparative evaluation of key elements in terms of their fire hazard potential, including fuel lines, the alternator, electrical wiring, the battery, the exhaust system, engine oil, and other associated components.

The analysis indicates that fuel lines represent the highest fire risk due to the potential for leakage of flammable substances and their proximity to ignition sources. The second highest risk category is associated with the battery and turbocharger, primarily due to electrical failure mechanisms (e.g., short circuits, thermal runaway) and elevated operating temperatures. Other components, such as the alternator, exhaust system, and additional engine subsystems, exhibit comparatively lower, yet still significant, levels of fire risk.

This comparative evaluation of component-level fire risk is graphically illustrated in Figure 10, which provides a clear visualization of the relative hazard ranking within the engine compartment.

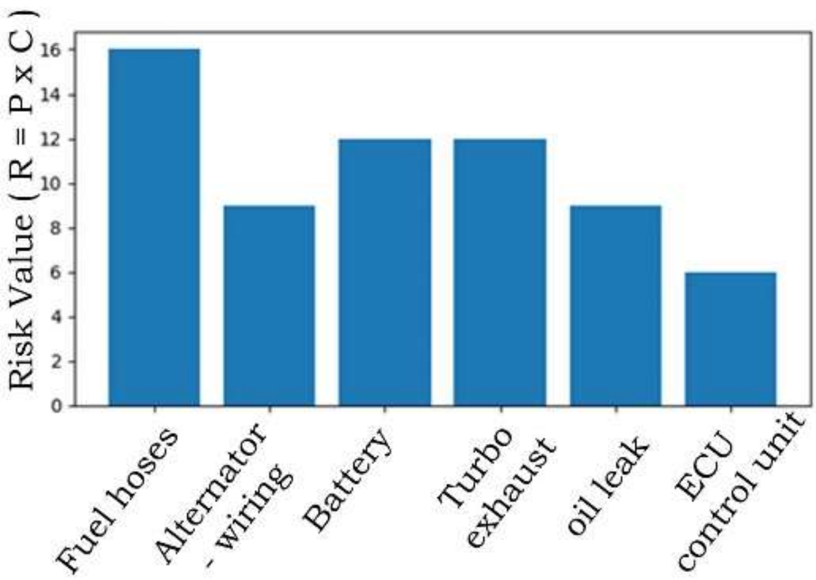

Fig.10. Engine compartment component risk chart

Pareto analysis represents an effective tool for identifying the most critical risk factors contributing to fire initiation. Based on the 80/20 principle, a limited number of components (e.g., the fuel system and electrical wiring) are responsible for the majority of fire incidents. This method enables the prioritization of preventive measures and the optimization of fire safety strategies within the engine compartment.

The application of Pareto analysis in this study allows for a clear identification of the most significant sources of fire risk and supports a more efficient allocation of safety measures. The results of this analysis are graphically illustrated in Figure 11, where the Pareto distribution of fire risk factors is presented.

Practical conclusion (80/20 principle).

To reduce or minimize the risk of engine compartment fire, it is necessary to focus on the following as a priority:

1. Fuel system tightness.

2. Battery and terminal condition.
3. Exhaust heat shielding.
4. Power wiring inspection.

Intervention in these areas will reduce the overall risk at the lowest cost.

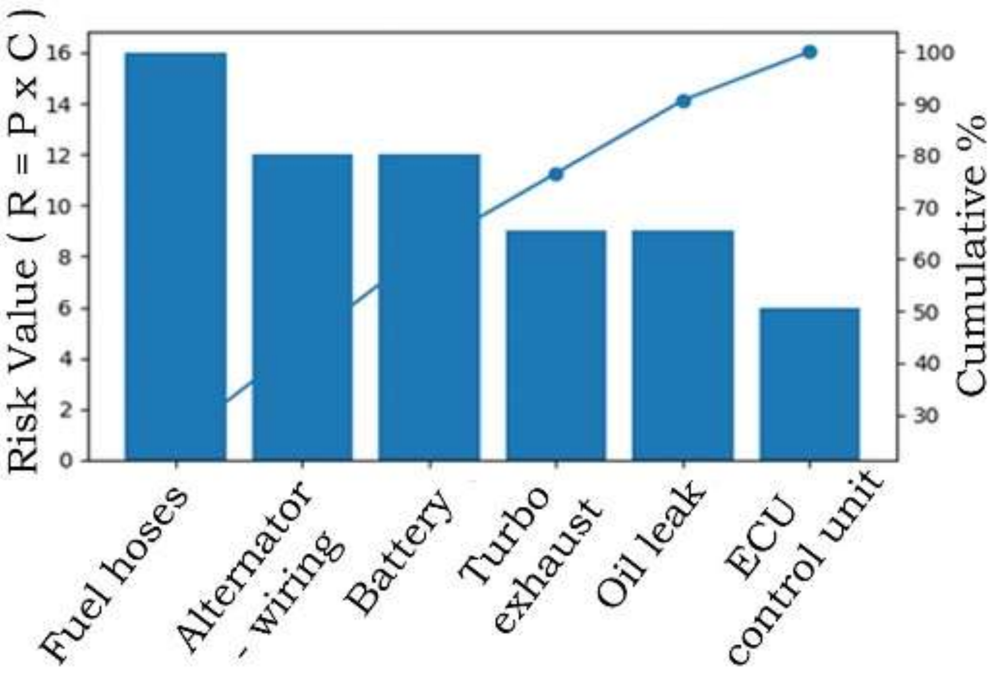

Fig.11. Pereto engine compartment risk analysis

4. CONCLUSION

The analysis of engine compartments in passenger vehicles indicates that up to 70% of fires originate as a result of mechanical failures, fuel leakage, or electrical short circuits. These factors represent the primary initiating mechanisms of fire within the engine compartment. Modern preventive strategies, including regular maintenance, intelligent monitoring through sensor-based systems, and predictive diagnostics, significantly contribute to the early detection of potential failures and risk conditions. In addition, the implementation of advanced safety technologies, such as automatic fire suppression systems and thermal fuses, plays a crucial role in reducing the probability of fire occurrence and mitigating potential damage.

This study provides a detailed examination of the passenger vehicle engine compartment, with a focus on identifying and characterizing the main fire risk sources. Individual components were systematically evaluated and classified according to their level of fire hazard, distinguishing between high-risk and moderate-risk elements. A quantitative assessment of fire occurrence probability and overall fire risk was carried out, enabling an objective evaluation of the hazard level. Based on these results, a risk distribution graph of engine compartment components and a Pareto analysis of fire risk factors were developed. The findings indicate that fuel lines represent the most significant contributor to fire risk, followed by the battery, turbocharger, exhaust system, and electrical wiring. Additional influencing factors include electronic control units and parameters such as oil pressure, which may indirectly contribute to hazardous conditions leading to fire initiation.

Furthermore, the study proposes a set of technical measures aimed at reducing fire risk, divided into design and operational approaches. From a design perspective, the application of thermal shields between high-temperature components and sensitive elements, the use of non-combustible or flame-retardant insulation for electrical wiring, and the integration of automatic fire suppression systems (e.g., aerosol-based modules) significantly enhance fire safety. From an operational perspective, regular inspection of fuel system integrity (e.g., every 10,000 km), monitoring of electrical wiring condition, and systematic cleaning and degreasing of the engine compartment are essential preventive measures.

Based on the results and conclusions obtained, a set of recommendations and proposed risk reduction measures are presented in Tables 3 and 4, which provide a practical framework for minimizing the risk of fire in the engine compartments of passenger vehicles.

FMEA (Failure Mode and Effects Analysis) we can see this analysis in Table 3, the method assesses risk according to the formula:

$$RPN = S \times O \times D \tag{9}$$

- S (Severity) – severity of the consequence (1-10),
- O (Occurrence) – probability of occurrence (1-10),
- D (Detection) – detection capability (1-10, 10 = difficult to detect),
- RPN – Risk Priority Number.

Tab. 3

Failure Mode and Effects Analysis

Component	**Failure**	**Consequence**	**S**	**O**	**D**	**RPN**
Fuel Hoses & Injection	Fuel leak	Rapid fire	9	6	6	324
Alternator + Wiring Short	Short circuit	Cable fire	8	5	5	200
Battery	Overheating	Oil ignition	7	6	6	252
Exhaust Pipe / Turbo	Short circuit	Local fire	7	5	5	175
Engine Oil Leak	Exhaust contact	Smoldering → flame	6	6	7	252
Control Unit (ECU)	Internal fault	Electrical ignition	5	3	6	90

Tab. 4

Recommended measures (reduction of RPN)

Component	**Measures**	**Impact**
Fuel Hoses	Metal braiding, regular pressure testing	↓O, ↓D
Exhaust	Heat shields, insulation	↓S
Battery	Terminal cover, fuses	↓O
Wiring	Non-flammable insulation	↓S
Oil	Tightness check	↓O

Acknowledgments

This research was supported by VEGA 1/0573/25 and KEGA 037TUKE-4/2024.

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Received 08.03.2026; accepted in revised form 17.05.2026