APPLICATION OF NATURAL GAS TO COMPRESSION IGNITION ENGINES

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Abstract

The paper presents general information on natural gas properties, reserves, production and distribution. Its proved reserves are estimated to have been ca. 6 trillion cubic feet. Main reserves are in Russia. Application of natural gas to automotive vehicles on the basis of literature review has been presented. European Union, US government and other countries have introduced directives for a natural gas application in the transportation sector. Because natural gas has a low cetane number, it cannot be directly applied to compression ignition engines. Such engines have to be adapted to dual fuelling. An assisted ignition with a pilot fuel quantity is necessary. Comparison of the spark ignition versus dual fuel engines, natural gas versus LPG and methane as well as choice of pilot ignition fuel have been discussed in the paper. Most of natural gas refueling stations is in Argentina. Progress in the field of dual-fuel natural gas engines has been presented. Application of natural gas as a fuel to internal combustion engines is useful regarding economy, emissions and worldwide energy strategy.

Keywords: *methane, natural gas resources, natural gas production, dual fuelling, compression ignition engine*

1. Introduction

Natural gas (NG) is one of the most important primary energy sources. Its reserves are about the same order of magnitude as petroleum reserves and they are much more evenly distributed on a global base.

Tab. 1. World natural gas reserves [2]

L.p.	Country	Reserves (trillion cubic meters)	Percent of world total
	World	171.03	100.0
	Top 20 countries	152.66	89.3
1.	Russia	47.57	27.8
2.	Iran	26.62	15.6
3.	Qatar	25.77	15.1
4.	Saudi Arabia	6.65	3.9
5.	United Arab Emirates	6.00	3.5
6.	United States	5.35	3.1
7.	Nigeria	4.98	2.9
8.	Algeria	4.56	2.7
9.	Venezuela	4.28	2.5
10.	Iraq	3.11	1.8

Proved world NG reserves were estimated at ca. 6 trillion cubic feet [1, 2]. Almost three-quarters of them are located in the Middle East and in the Former Soviet Union. Location of the natural gas main reserves are given in Table 1. The biggest producer of natural gas is Russia (Table 2). About 80% of the world natural gas production is consumed locally.
Natural gas has been used to fuel vehicles since the 1930's and it has gathered renewed interest in the transportation sector since the beginning of the 1990's. In transport application it is called NGV (Natural Gas for Vehicles).

The main constituent of natural gas is methane (80-98% – depending on the extraction source). Other constituents are: ethane (1-8%), propane (do 2%), butane and pentane (less than 1%) [1]. Natural gas contains also nitrogen and carbon dioxide (0.2-1.5%) and small quantities of sulphur compounds (hydrogen sulphide and mercaptans). Natural gas is non-toxic, odourless and non-corrosive. It is lighter than air and is slightly soluble in water.

Tab. 2. World natural gas production [3]

L.p.	**Country**	**Production (billion cubic meters)**
1.	Russia	16,45
2.	Canada	5,29
3.	Algeria	2,27
4.	Netherlands	2,20
5.	Indonesia	1,95
6.	Iran	1,74
7.	Norway	1,55
8.	Saudi Arabia	1,52
9.	Malaysia	1,52
10.	Mexico	1,04

As a fuel natural gas is used:

- in gaseous form (at ambient temperature and under high pressure – 20 MPa) and is called compressed natural gas (CNG),
- in liquid form (cooled to the temperature of -161oC and at atmospheric pressure) and is called liquefied natural gas (LNG).

NGV can be considered to be a clean fuel. NGV vehicles emit almost no hydrocarbons with more than four atoms of carbon. In particular, no aromatic compounds are detected in the exhaust. Vehicles fuelled with NG emit more methane, but less CO_2, than those fuelled with conventional fuels. Of all hydrocarbon compounds used as motor fuels, methane has the highest knock resistance. Its octane number is ca. 130. Methane combustion is relatively slow, what contributes to less combustion noise. Methane has also reasonable-low flame temperature what limits formation of nitrogen oxides.

Existing quality standards for CNG [2] are:

- ISO 15403:2000 "Natural gas – Designation of the quality of natural gas for use as a compressed fuel for vehicles"
- SAE J1616:1994, "Recommended practice for compressed natural gas vehicle fuel"

Physico-chemical properties of natural gas are given in Table 3.

The potential for low exhaust gas emission indicates that natural gas should be preferred in city traffic (buses, taxis etc.). Also for technical reasons – it is not very suitable for long-range transport. Natural gas-powered vehicles (dedicated or modified) are commonly called NGVs (Natural Gas Vehicles). Already more than four million taxis, buses, heavy-duty vehicles, private cars and specialist vehicles are running on natural gas in 65 countries around the world. The leading countries are given in Table 4. The number of refuelling stations in the world is ca. 9 000. Natural gas refuelling stations can be divided in two groups: public and private refuelling stations. The first are accessible for anyone, the second are in possessing of large fleet owners. Exist also private refuelling systems installed at home but they are not very popular.

Tab. 3. Physical and chemical properties of natural gas as engine fuel [4]

Properties	**CNG**	**LNG**
Density (in the conditions of storage), kg/m^3	160 (15^oC, 20 MPa)	425 (-150^oC, 0.3 MPa)
Heating value (in the conditions of storage), MJ/kg (MJ/dm^3)	48.80 8.44	49.30 20.95
Heating value of the stoichiometric air-fuel mixture, $\lambda=1$, kJ/m^3	3310	3310
Boiling point, ^oC	-162	-162
Autoignition point, ^oC	540	540
Heat of vaporization, kJ/kg	510	510
Stoichiometric ratio, kg /kg	17.1	17.1
Octane rating MON	105	105
Octane rating RON	110	110

Tab. 4. Natural gas vehicles and refuelling stations in the world [5]

Country	**Natural Gas Vehicles (total)**	**Natural Gas Refuelling Stations (total)**
Argentina	1 457 118	1 452
Brazil	1 011 206	1 138
Pakistan	700 000	766
Italy	382 000	521
India	222 306	192
USA	130 000	1 340
China	97 200	3 55
Colombia	72 136	168
Ukraine	67 000	147
Iran	63 779	96
Egypt	61 590	91
Venezuela	44 146	149
Russia	41 780	213
Bangladesh	41 314	122
Armenia	38 100	60
Bolivia	35 810	62
Germany	27 200	622
Japan	24 648	288
Canada	20 505	222
Poland	771	28

2. Spark Ignition versus Dual Fuel

Dual fuel engine takes advantage of inherent efficiencies of compression ignition engine, but with reduced diesel fuel consumption, what results in an engine, which is both more powerful than dedicated spark-ignited natural gas engine, but with generally better emissions than dedicated compression ignition engine.

In comparison with spark-ignited gas engine, dual fuel engine has [6-8]:

- extended life and long-term reliability
- better fuel economy (lower BSFC)
- better startability in low temperature (cold start)

and:

- requires fewer NG tanks
- can be fuelled solely with diesel fuel, in case of NG shortage
- is more resistant to knocking combustion
- is less noisy.

Moreover, spark-ignited gas engine has higher cycle-to-cycle variations, leading to deterioration of efficiency and power.

As far as economy aspects are concerned, NG engine installation costs in busses refund sooner than LPG SI or LPG + DF in C.I. engines (SI –NG a little sooner than dual fuel) [8].

3. Natural Gas versus LPG and Methane

A comprehensive study on application of three different gases to dual-fuel engine was carried out in [9]. The pilot fuel was diesel fuel and applied gases were: NG, LPG and pure methanol. The following conclusions were drawn from these experiments:

- Dual-fuel engine fuelled with methane produces higher power and better efficiency than the one fuelled with NG, followed by LPG.
- Methane gives higher resistance to knock than NG, while LPG is the most prone to knock (the onset of knock is associated with drop in thermal efficiency and power).

LPG as the main fuel produces the highest combustion noise followed by methane and NG.

4. Choice of Pilot Fuel

In NG dual-fuel engine the pilot fuel, which generally is diesel fuel, may be replaced by renewable biofuel as plant oil or FAME. In [10] two pilot biofuels were investigated: neat rapeseed oil and rapeseed oil (RO) methyl ester (RME) and compared with diesel fuel.

The following conclusions may be drawn from this investigation:

- At low load, ignition delay of RO was longer and at high load shorter than for diesel fuel
- Ignition delay of RME was shorter than for diesel fuel in the whole range of load.
- Brake fuel conversion efficiency was the best for neat RO, especially at middle sped in the whole range of load, and for RME almost the same as for DF.
- Hydrocarbon emissions of dual-fuel engine were similar for RO and DF and lower for RME.

Taking into account the above statements and advantages of RME in comparison with RO, there is no doubt that RME can replace DF as a pilot fuel.

5. New Generation of Dual-Fuel Natural Gas Engines

First dual-fuel engine built Rudolf Diesel (1896) in Maschinenbaufabrik Augsburg- Nürnberg, MAN. He injected directly petroleum and natural gas into C.I. engine (called after him diesel). This was the idea of gas-diesel engine. Further approach to dual-fuelling of internal combustion engines was carried out by Karim [11-13] in Canada and by Zabłocki in Poland [14]. Karim carried out a lot of experiments and showed topic problems, which should be overcome in the field of combustion in DF NG engine. Zabłocki worked out a theoretical background of dual fuelling and showed how CI engine should be adapted to fuelling with natural gas.

New generation [6] of dual-fuel natural gas engines is fitted with electronically controlled multipoint part-injected sequential NG fuel system and Electronic Control Unit (ECU) that integrates with existing Electronic Control Modul (ECM). ECU precisely controls both fuels injection (metering and timing of injection of each fuel) and optimizes combustion in view of emission and efficiency.

US Department of Energy supports R&D work on dual-fuel heavy duty vehicles for transportation. In Cummins ISX diesel engine high pressure direct injection NG system was installed [15]. Engine was turbocharged, charge air and EGR coolers were applied. Analogically electronically controlled is Caterpilar engine that uses NG or propane.

Bus and light-duty vehicles engines fuelled with NG are produced in two versions/types:

- spark ignition CNG engines
- dual-fuel engines (diesel fuel is pilot ignition fuel).

Both types of CNG engines are applied in buses by such companies as Cummnis, John Deere, Detroit Diesel, Volvo, MAN, Caterpillar, Blohm & Voss, MAN B & W Gasmotoren [16], Cummins and Westport (2nd type) [17].

Westport Co. presented high pressure direct injector which injects simultaneously NG and diesel fuel [18]. The injector has two needles: a needle within a needle with separate injector holes for each fuel. The diesel fuel is injected some milliseconds earlier than natural gas; its autoignition is the source of instantaneous ignition of natural gas. Due to that, mixture of both fuels burns quickly in air. The Westport injector was applied in Detroit Diesel 6V-92 TA engine and is planned to be applied in the QSK-19 Cummins prototype [18].

Presently in Europe and in the United States cars and pick-ups are produced that are fuelled with LPG and/or CNG and also occur with bi-fuel engines, which may be fuelled with both fuels LPG/NG and gasoline [19]. EEC established regulations for new vehicles and also established standards for LPG and NG systems [20]. Also standards for LPG and NG fuels used as standard fuels in EURO tests were introduced [21].

The present situation and prospects of CNG as an automotive fuel was reviewed in reference [22]. In many towns exist fleets of city busses fuelled with CNG. There are also a couple of CNG filling stations.

6. Conclusions

Application of natural gas as a fuel to internal combustion engines is useful regarding economy, emissions and worldwide energy strategy.

Analysis of fuelling spark ignition versus compression ignition engine with natural gas results in that, that it is more convenient to apply it to this last type of engines. Fuelling with natural gas does not demand any change of compression ignition engine design as in the case of spark ignition engine, of which materials should be more resistant to wear and compression ratio should be decreased, but only addition of fuel installations, what is necessary also for spark ignition natural gas engine. In comparison with diesel, natural gas dual fuel engine produces less particulate matter, carbon dioxide and nitric oxides. Application of cool EGR may decrease emission of carbon oxide and hydrocarbons, which are normally higher than for diesel operation. For application of natural gas to automotive dual fuel engines, of which operation parameters are changing in a wide range, control parameters of the engine, mainly such as pilot diesel quantity and its timing as well as natural gas – air equivalence ratio, should be optimised from the point of view of efficiency and emissions.

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ANALYSIS AND EVALUATION OF RISK IN A TRANSPORT SYSTEM

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Abstract

The dangers originating within the vehicle usage process, resulting from incorrect operation of their braking subsystems have been evaluated in the paper.

The subject of the analysis is influence of the forcing factors on occurrence of the damages to the bus braking subsystems. The operation and maintenance factors affecting the technical object elements cause unfavourable changes of the values of their significant features, as far as the vehicle operation is concerned, causing the damages. Among the forcing factors it is possible to distinguish the ones resulting from improper action of a human and those resulting from reaction of the environment to the technical objects.

If the originated damages are not interconnected to one another by a cause and effect link, what means that they are independent and occur randomly, such damages are specified as primary ones herein. However, if the damages are dependable and they originate due to human faults in the process of repairing the primary damage or due to driver's faults within the vehicle usage process then they are secondary ones.

The vehicle damages at the operation and maintenance stage may occur due to human's faults:
- *within the service process (diagnostic faults, parts dismantling and assembling faults, using wrong spare parts – e.g. non original ones, using substitutive repair means),*
- *within the usage process (operator-driver's faults, passengers' faults),*
- *within other processes (reactions coming from the environment of the technical object).*

The studies have covered a randomly chosen sample of the technical objects being operated and maintained within a real urban bus transportation system.

Keywords: *transport system, safety, reliability, maintenance, failures*

1. Introduction

It was attempted herein to evaluate the dangers originated in the process of using vehicles, resulting from their operation in a state of limited serviceability. Based on the analysis of the relevant literature and the results obtained from our own studies it was found that the dangers created by the vehicles being used within transport systems are effects of an interaction of various forcing factors. There factors may be divided into:

a) working (within the system) – forcing factors affecting vehicle as a result of carrying out useful functions (which depend on the vehicle operations), such as:
   - torque,
   - moments of inertia,
   - compression and working pressure,
   - heat emitted due to mating of components,
   - friction,
   - etc.

b) external – forcing factors characterising influence of the environment on a vehicle (they do not depend on the vehicle operation):
   - improper behaviour of co-users of the roads,
   - inappropriate road infrastructure,
   - inappropriate road surface condition,
   - unfavourable atmospheric conditions,

- etc.

c) human engineering – forcing factors affecting the vehicle due to human actions such as operator's faults:
   - driver's ones
     - improper steering of a vehicle,
     - driving speed not adjusted to the road conditions,
     - wrong estimation of the situation.
   - serviceman's ones
     - wrong diagnosis (pre- and after-repair),
     - wrong execution of the repairs and technical services.

An exemplary arrangement of the reasons for the damages caused to the automotive vehicles is presented in the Fig. 1 [10].

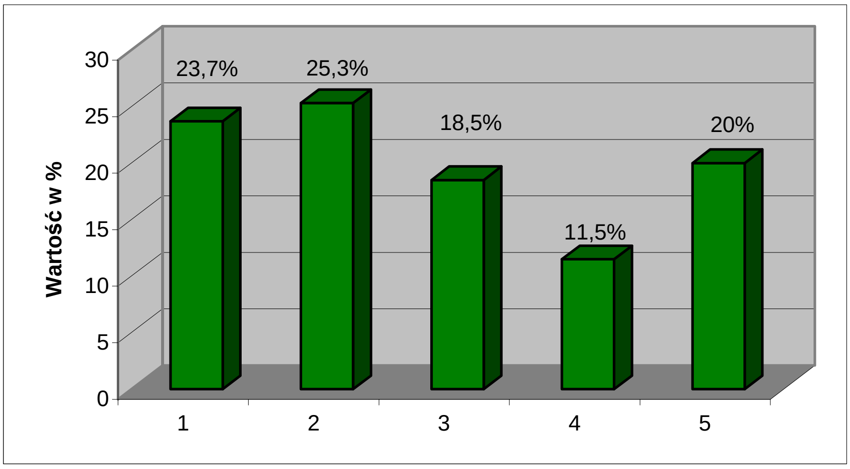

Fig. 1. Frequency of the occurred reasons for the components damages

1. Repair faults,
2. Usage faults,
3. Influence of the environment,
4. Damage of mating components,
5. Others.

The damages to the vehicle subsystems occurred during the usage process within the transport systems lead to dangerous events causing threats. A damage at work is defined as exceeding admissible limiting values by significant features describing the elements. When carrying out a task in a state of limited serviceability resulted from exceeding the limiting values of the significant elements features, a vehicle may undergo a failure or a road accident, followed by threats to: the human health and life, the vehicle and the environment. ***A threat****, is to be interpreted as a conditional possibility of generating losses due to occurrence of a single undesirable event* [3, 7]. *However,* ***the undesirable event (dangerous one)*** *is described as such an event which may cause a damage* [3].

Whereas, ***a damage*** *according to* [3, 7] *is defined as a physical injury to health, impairment of a property or degradation of the environment.*

The threat degree is evaluated basing on the evaluation of the risk level value.

The risk is a combination of occurrence of an undesirable event and the effects measured by the extent of the losses caused by it.

One of the most significant risk measures is probability of occurring losses in the assumed time interval of the system functioning ⟨H-TO-E⟩ (Human-Technical Object-Environment) under investigation.

The risk measures, described in the relevant literature, are generally used to describe its levels, assuming that the losses occur suddenly within short time intervals and it happens for various random reasons.

Having analysed the results of the operation and maintenance investigations related to the moments of the damage occurrence it was found that the damage set may be divided into primary and secondary damages.

It results from the fact that the occurrence moments of the same components damages are concentrated sequentially after the occurrence of a single damage to a component.

As it can be seen in the Fig. 1 the first of the damages, occurred in the moments t_i, cause the sequence of further damages to the same component in short intervals. These damages were called ***primary*** ones. Whereas, the further damages, with a finite number of repetitions, occurring in the moments t_{ij}, were called ***secondary*** ones.

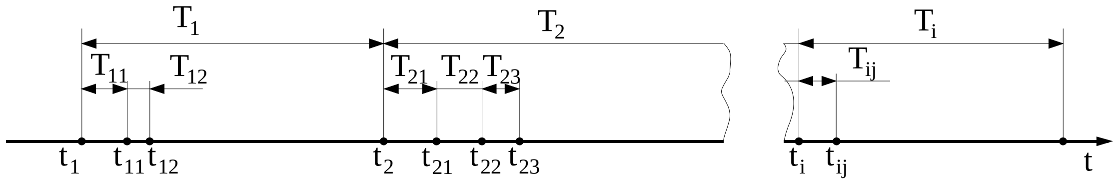

Fig. 1. The time intervals between the primary and secondary damages.

t_i – moments of the primary damages occurrence,
t_{ij} – moments of the secondary damages occurrence,
T_i – time intervals between the moments of the primary damages occurrence,
T_{ij} – time intervals between the moments of the secondary damages occurrence.

The primary damages do not depend on one another and they happen randomly (they are not interrelated by cause and effect links). The secondary damages are dependable, because their occurrence depends on a previous occurrence of a primary damage and on the outcome of its improper repair or an improper repair of the next secondary damage.

As it results from the above statement, the occurrence of an event being a secondary damage is conditioned by the occurrence of a primary damage. This may be formulated as follows:

$$P(A_{ti}/B_{tij}) > P(B_{ti}) \qquad (1)$$

where: $t_{ij}<t_i$
$t_i \in [0, t]$
$P(B_{tij}) \geq 0$

This means that the probability of the occurrence of a secondary damage A_{ti} conditioned by the occurrence of a primary damage B_{tij} is greater than the probability of the occurrence of a primary damage B_{tij}.

The secondary damages at the operation and maintenance stage may happen:

- within the service process (faulty dismantling and assembling the components, using wrong spare parts – e.g. non original ones, using substitutive repair means, lack of ensuring adequate quality level of the service and repair activities, improper diagnostic operations etc.),

- within the usage process (operator-driver's faults, inappropriate behaviour of the passengers or people who are nearby the vehicle e.g. those at a bus stop, those who run across the road),
- due to the environment affecting a technical object.

The secondary damages form a significant value in the total number of the damages.

The Table 1 shows percentage of the selected vehicle subsystems, the dames of which were reason for road accidents. As it may be noticed, the Table 1 proves that the greatest number of the damages is related to the braking subsystem.

Table 1. Percentage of the number of the damages to the selected vehicle subsystems in the total number of the damages, causing road accidents in Poland between 2002 and 2004 [8]

Name of the damaged subsystem	Percentage of damages per years		
	Year 2002	Year 2003	Year 2004
braking	18%	38%	24%
suspension	14%	25%	21%
driving	23%	6%	7%
steering	18%	6%	14%

As it can be seen the braking subsystem plays an important role in a vehicle, because its correct working is significantly decisive for the vehicle active safety. For that reason this subsystem was called significant one from the point of view of the vehicle operation safety and it was taken as an object for further investigations.

2. PURPOSE

The purpose of this paper is to evaluate the influence of the damages to the braking subsystems of the vehicles being operated and maintained within a transport system on the risk level value being borne when using a vehicle.

3. INVESTIGATION OBJECT

The investigation object are damages to the braking subsystems of the buses being operated and maintained within an urban transport system. While the investigation subject is the influence of these subsystem damages on the risk level value.

4. INVESTIGATION METHODOLOGY

The operation and maintenance investigations refer to the elements of the bus braking subsystems and to the moments they occur. Respective busses to be investigated were selected randomly. The operation and maintenance investigations were performed by means of the passive experiment method in real operation and maintenance conditions.

28 buses, 7 of each type, were selected for the investigation purposes. The investigation results cover a year-long operation and maintenance period.

5. RISK LEVEL EVALUATION METHODOLOGY

As a result of the analysis of the selected methods of risk evaluation (FMEA, ET/OU, FMECA) of a danger occurrence when operating and maintaining the means of an urban transport system, FMEA method, due to its easiness to apply with unanimous possibility of precise representation, was chosen for the investigation aims.

The FMEA method is to determine probability of the occurrence of damages and failures and of the effects related to their occurrence referred to the system ⟨H-TO-E⟩ or its subsystems under investigation.

This method is to set the risk level of occurrence of dangerous events (R) depending on the probability of occurrence of a damage or failure of a subsystem of the technical object (P), evaluation of the index of the operator's faults effects (Z) and the index of a damage detectability (W).

A method related to the probability of detection of a damage to the technical object subsystem was used herein.

Depending on the real need the risk level evaluation with FMEA method is carried out in more or less detailed way. It is done through setting the risk value R [10], according to the following dependence (1):

$$R = P \cdot W \cdot Z \tag{2}$$

where:

R – index of risk evaluation,

P - index of probability of a damage occurrence,

W - index of a damage detection,

Z - index of the effects of the damages to the vehicle subsystem (component) or of an operator's faults outcomes,

In the risk level evaluation method, as per FMEA, little changes to the values of the indices of probability of a damage occurrence, detection of a damage by a driver and effects of a damage to the subsystem (component) generate significant changes to the risk value R, described with the dependency (1). The risk level may also take significant values in such a case when the value of one of the elements of the product P*W*Z is high. Therefore, when evaluating the risk value, the values of all the indices (dependence 1) are to be analysed. That is why it is needed to evaluate the influence of the damages to the subsystem components on its correct operation and to determine the effects of these damages.

In order to calculate the value of the risk index R, the values of the indices P, W, Z are to be standardized within the range $\langle 1 \div 10 \rangle$.

Further actions depend on the risk level value R [7]. High value of the risk level R should be the basis for taking actions aimed at minimizing the occurrence of a damage [7]. A proposal of exemplary values of the indices P, W, Z, used to determine the risk value are entered in the Table 2.

Table 2. Exemplary values of the P, W, Z indexes applied to evaluate the risk [7]

Failure occurrence probability – failure may take place (occurrence)	Detectability index – fault may be detected (occurrence)	Failure effects index - interaction (significance)

P		W		Z	
Improbable	1	High probability	1	Almost imperceptible	1
Very slightly probable	2÷3	Moderate probability	2÷5	Slight load	2÷3
Slightly probable	4÷6	Slight probability	6÷8	Moderately medium fault	4÷6
Moderately probable	7÷8	Very slight probability	9	Severe fault	7÷8
Highly probable	9÷10	Improbable	10	Extremely severe fault	9÷10

Following the analysis of the literature and our own investigations, the Table 3 shows proposed values of the indices applied herein to evaluate the risk, basing on which appropriate values are adopted. The assigned values depend on the technical object condition, operator's knowledge and efficiency of the damage detection.

Table 3. Assumed correlation between the number of the assigned points and the event occurrence probability value

Number of points	Event occurrence probability	Probability value
1	Very slight	0,001÷0,0099
2-3	Slight	0,01÷0,099
4-5	Moderate	0,1÷0,199
6-7	Frequent	0,2÷0,29
8-9	High	0,3÷0,35
10	Very high	> 0,35

L_u index representing the numbers of the damages per each 100 000 kilometres was also applied in the paper to let us take into consideration percentage of the secondary damage in the total number of the damages.

$$L_u = (L / P) \cdot 100\,000 \text{ km} \tag{3}$$

where:
L – number of the damages to the braking subsystem,
P – number of the kilometres travelled by a vehicle.

6. INVESTIGATION RESULTS

Twin pipe, twin circuit pneumatic braking systems are applied in the buses taken for the investigations. Some damages occur to the components of the braking subsystems thus causing dangers to the system operation ⟨H-TO-E⟩ (Table 4).

Table 4. Significant effects of the damages to the braking subsystem in the buses of the following makes: MAN NL223, JELCZ JM181M/1 and VOLVO B10BL

Description of the effects caused by damages to a component in a subsystem	**Description of a damaged component**

Sudden drop in pressure in the pneumatic system of the braking subsystem	- pneumatic system pipe, - relay valve (APH), - compressor,
Too high or too low pressure value in the pneumatic system	- pressure regulator,
Excessive pressure jump values in the pneumatic system	- pressure regulator,
Blocking wheels when brake partially applied in an unloaded vehicle	- ABS, - pressure regulator,
Blocking wheels due to blocked servo mechanisms	- relay valve (APH),
Too high or too low braking force value on the respective wheels	- main brake valve - circuit I or II, - pressure regulator, - corrective valve, - relay valve (APH), - pneumatic system, - four-circuit safety valve - disc or drum assemblies to transfer braking force to the vehicle wheels,
Too intense braking of a wheel of the front or rear vehicle axle	- valve accelerating vehicle brake release, - pressure regulator, - main brake valve,
Problems to unblock the wheels of the front or rear axle after releasing the brake pedal	- valve accelerating brake release,
Delayed braking moments of the rear axle wheels in relation to the front axle wheels	- main brake valve, - valve to control braking force, - relay valve (APH),
No braking force on the wheels when vehicle brake is applied	- diaphragm-spring servo mechanism, - expander, - valve to control braking force, - relay valve (APH).

On the basis of the results obtained from the operation and maintenance investigations, the numbers of the primary and secondary damages to the bus braking subsystems were determined and the values of R and L_u were calculated.

The selected investigation results and calculations are presented in the Table 5.

Table 5. Values of the risk indices (R) and of the index (Lu) for the selected buses braking subsystems

Bus number	**Code of the damaged component**	**Number of the primary damages**	**Number of the secondary damages**	**Value of the indices for the real number of the secondary damages**		**Value of the indices for 75% of the number of the secondary damages**		**Value of the indices for 50% of the number of the secondary damages**		**Value of the indices for 0% of the number of the secondary damages**	
				R	**Lu**	**R**	**Lu**	**R**	**Lu**	**R**	**Lu**
Buses Jelcz M11											
1	A	0	0	18	68,51909	18	62,6589	18	56,79872	18	45,07835
	B	15	9	**90**		**80**		**70**		**60**	
	C	5	3	**64**		**64**		**64**		**64**	
	D	1	0	24		24		24		24	
	E	2	1	42		42		42		42	

Table 5. Values of the risk indices (R) and of the index (Lu) for the selected buses braking subsystems cont.

Bus number	**Code of the damaged component**	**Number of the primary damages**	**Number of the secondary damages**	**Value of the indices for the real number of the secondary damages**		**Value of the indices for 75% of the number of the secondary damages**		**Value of the indices for 50% of the number of the secondary damages**		**Value of the indices for 0% of the number of the secondary damages**	
				R	**Lu**	**R**	**Lu**	**R**	**Lu**	**R**	**Lu**
Buses Jelcz M11											
2	A	0	0	18	38,63324	18	34,87723	18	31,12122	18	23,6092
	B	9	6	**60**		**50**		**40**		**30**	
	C	1	1	32		32		32		16	
	D	0	0	24		24		24		24	
	E	1	0	24		24		24		24	
3	A	0	0	18	24,4858	18	22,25982	18	20,03383	18	15,58187
	B	6	4	**40**		**40**		**30**		**30**	
	C	1	0	18		18		18		18	
	D	0	0	24		24		24		24	
	E	0	0	24		24		24		24	
4	A	0	0	18	38,84551	18	33,98982	18	29,13413	18	19,42276
	B	6	9	**60**		**60**		**50**		**50**	
	C	3	1	**48**		**48**		**32**		**32**	
	D	0	0	24		24		24		24	
	E	1	0	21		21		21		21	
5	A	0	0	18	38,52221	18	35,77063	18	33,01904	18	27,51587
	B	11	4	**60**		**60**		**50**		**30**	
	C	3	2	**48**		**48**		**32**		**32**	
	D	1	0	24		24		24		24	
	E	0	0	21		21		21		21	
6	A	0	0	18	85,07018	18	76,03148	18	66,99277	18	48,91536
	B	18	11	**120**		**100**		**60**		**30**	
	C	4	6	48		48		32		32	
	D	0	0	24		24		24		24	
	E	1	0	21		21		21		21	
Buses Jelcz JM181											
7	A	2	0	36	40,82979	36	37,68903	36	34,54828	36	28,26678
	B	7	5	**50**		**50**		**40**		**40**	
	C	6	3	64		64		64		48	
	D	0	0	24		24		24		24	
	E	3	0	42		42		42		42	
8	A	0	0	18	35,59682	18	31,3252	18	27,05358	18	18,51034
	B	2	4	30		30		20		20	
	C	5	5	**64**		**64**		**48**		**48**	
	D	1	0	24		24		24		24	
	E	5	3	**84**		**84**		**63**		**63**	
Buses Ikarus IK280											
9	A	0	0	18	11,95797	18	10,83691	18	9,715849	18	7,47373
	B	5	3	40		40		40		40	
	C	0	0	16		16		16		16	
	D	0	0	24		24		24		24	
	E	0	0	21		21		21		21	
10	A	0	0	18	17,87717	18	14,22047	18	13,81417	18	13,00158
	B	2	0	20		20		20		20	
	C	4	1	48		48		48		48	
	D	0	0	24		24		24		24	
	E	1	0	21		21		21		21	

On the basis of data included in the Table 5 significant components of the braking subsystem from the point of view of the operation risk were determined.

Table 6. List of the significant components of the braking subsystem.

Code of the damaged component	Name of the damaged component	Significance level
B	pneumatic system	1
C	working components (discs – pads, drum – brake shoe)	2
E	other components	3
D	servo mechanism	4
A	main brake valve	5

7. INVESTIGATION RESULTS ANALYSIS AND CONCLUSIONS

From the data presented in the Table 5 it results that the most significant influence on the risk level value in the braking system have the damages to such subsystems as: pneumatic system of controlling brake shoe spreader and working elements (discs – pads, drum – brake shoes). The risk level reaches the highest values in case of the vehicles of Jelcz M11 type.

Based on the investigation results shown in the Table 5 (1B, 3B, 4B, 6B, 7B) it may be concluded that the number of the secondary damages occurred is significant. The highest percentage of the secondary damages in total number of the damages is characteristic for the buses of Jelcz M11 make.

It is worth mentioning that when reducing the number of the secondary damages to the subsystems components the risk level value is reduced as well. Even little changes to the number of the secondary damages lead to reduction of its value. By reducing the number of the secondary damages by 50% we reduce the risk level value even by 1/3. Whereas, elimination of the secondary damage in case of the pneumatic system of the bus No. 2 would allow us to obtain significant reduction of the risk level value, even by as many as 50%.

From analysing the source data it results that the secondary damages to the components of the bus braking subsystem should be eliminated especially within the service and repair process. It may be achieved by:

- correct diagnostic process,
- applying adequate spare parts,
- applying adequate repair means,
- observing scheduled times for surveys and replacements,
- correct assembling and disassembling.

Carrying out the investigation for longer period would allow us to determine the significant components of the subsystem. When performing the research, attention should be paid to these danger effects which negatively affect human organism. It is quite an important issue, because these effects may subsequently lead to new dangers.

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