

INTERNATIONAL SCIENTIFIC JOURNAL

trans & MOTAUTO WORLD

YEAR VII, ISSUE 3/2022

ISSN PRINT 2367-8399

ISSN WEB 2534-8493



SCIENTIFIC TECHNICAL UNION OF MECHANICAL ENGINEERING "INDUSTRY 4.0"
108 RAKOVSKI STR., SOFIA 1000, BULGARIA

PUBLISHER:

**SCIENTIFIC TECHNICAL UNION OF MECHANICAL ENGINEERING
INDUSTRY-4.0**

108, Rakovski Str., 1000 Sofia, Bulgaria

tel. (+359 2) 987 72 90,

tel./fax (+359 2) 986 22 40,

office@stumejournals.com

www.stumejournals.com

ISSN PRINT 2367-8399

ISSN WEB 2534-8493

YEAR VII, ISSUE 3 / 2022

EDITORIAL BOARD

CHIEF EDITOR

Prof. Petar Kolev, Bulgaria

MEMBERS:

Prof. Ahmet H. Ertas, TR
Prof. Aleksandar Kostikj, MK
Prof. Andrey Ferenets, RU
Prof. Angel Dimitrov, BG
Prof. Beti Angelevska, MK
Prof. Dainis Berjoza, LV
Prof. Dan Scarpete, RO
Prof. Daniela Todorova, BG
Prof. Emilia Andreeva-Moschen, AT
Prof. Hristo Stanchev, BG
Prof. Igor Penkov, EE
Prof. Igor Smirnov, UA
Prof. Igor Taratorkin, RU
Prof. Iliyan Lilov, BG
Prof. Lech Sitnik, PL
Prof. Ljudmila Boyko, UA
Prof. Madaminjon Aripdzanov, UZ
Prof. Martin Kendra, SK

Prof. Massimo Borghi, IT
Prof. Miho Mihov, BG
Prof. Murat Dogruel, TR
Prof. Natalia Sidenko, LV
Prof. Natasa Tomic-Petrovic, RS
Prof. Nikolay Georgiev, BG
Prof. Nikolay Ovchenkov, RU
Prof. Oleg Sharkov, RU
Prof. Pepo Yordanov, BG
Prof. Polatbeg Zhunisbekov, KZ
Prof. Rinat Kurmaev, RU
Prof. Rosen Ivanov, BG
Prof. Sanjin Troha, HR
Prof. Teymuraz Kochadze, GE
Prof. Tomaz Morchadze, GE
Prof. Vadim Zhmud, RU
Prof. Valyo Nikolov, BG
Prof. Zoran Jovanovic, RS

RESPONSIBLE SECRETARY:

Prof. Nikolay Tonchev, Bulgaria

CONTENTS

TRANSPORT TECHNICS. INVESTIGATION OF ELEMENTS. RELIABILITY

Influence of profile modifications on the scuffing load capacity of high contact ratio gears Jaacob Vorgerd, Manuel Joop, Peter Tenberge	85
LNG fueled ship type "C" storage tank pressure rise particularities related to the bunkering flow Delyan Hristov	91
Optimal length of a railway curve for a given design speed Matey Iliev	94
Disturbance rejection in a one-half vehicle suspension using a fuzzy controller Katerina Hyniova	98

TRANSPORT. SAFETY AND ECOLOGY. LOGISTICS AND MANAGEMENT

Application of photogrammetry in the analysis of vehicle collision processes Teljko Šarić, Krešimir Ećimović, Andrej Kunštek, Tomislav Kučinić	103
Qualitative traffic indicators analysis and optimization model for traffic operations in urban zone Gëzim Hoxha, Ramë Likaj, Astrit Sallauka	110
Traffic management system in the city of Rijeka Siniša Vilke, Frane Tadić, Borna Debelić, Davor Mance	115
Efficiency of intervention technologies for snow removal equipment on public roads Sebastian Petru Boboc	120
Segmentation of railway transport images using fuzzy logic Balovsyak S.V., Derevyanchuk O.V., Derevianchuk Ya.V., Tomash V.V., Yarema S.V.	122
Measures for improving pavements roughness Razvan Buliga	126

VEHICLE ENGINES. APPLICATION OF FUELS TYPES. EFFICIENCY

Study of the effects on engine fuel consumption generated by turbocharger performance Dimitar Popov	132
---	-----

Influence of profile modifications on the scuffing load capacity of high contact ratio gears

Jaacob Vorgerd^{1*}, Manuel Joop², Peter Tenberge¹

Ruhr-University Bochum, Germany¹

Envision Energy CoE GmbH, Germany²

jaacob.vorgerd@ruhr-uni-bochum.de, peter.tenberge@ruhr-uni-bochum.de

Abstract: Scuffing is a spontaneous gear failure mechanism resulting in a disrupted surface. Scuffed gears are more sensitive to dynamic excitation and friction. Besides the lubricant and the material, the scuffing load capacity is mainly dependent on the gear geometry. High contact ratio gears exhibit a lower load carrying capacity due to an increased dissipation of frictional heat in the outer mesh positions. In this paper this phenomenon is addressed with experiments and simulative analysis. Based on these works, recommendations for adequate profile modifications are derived to maximize the load carrying capacity regarding scuffing of high contact ratio gears.

Keywords: CYLINDRICAL GEARS, SCUFFING, GEAR FRICTION, FLASH TEMPERATURE, PROFILE MODIFICATION

1. Introduction

Warm scuffing is a spontaneously occurring, adhesive damage mechanism of highly loaded slide-roll contacts, e.g. in gears [1, 2]. Scuffed surfaces are more sensitive to vibration and exhibit poorer frictional properties. The verification of the scuffing load capacity is often mandatory in the design process of drive systems. With regard to increasing power densities, especially in high-speed electric mobility drives, high contact ratio gears are preferably used. Extending the length of the usable involute leads to improved dynamic properties with lowered excitation of vibrations but it can be more susceptible to scuffing [2–5]. In this paper, experimental and simulative results of a high-speed test rig for cylindrical gears are presented and used to demonstrate the load sensitivity regarding scuffing of high contact ratio gears. Moreover, the influence of profile modification on the local loads during a full gear mesh are shown. On this basis, recommendations for adequate profile modifications to improve the scuffing load capacity are derived.

2. State of the art

2.1 Scuffing of cylindrical gears

In the case of scuffing, contact points weld locally and are immediately torn apart due to the meshing kinematic [6, 7]. The damage that occurs is always found in pairs (pinion/wheel) at the outer mesh positions A or E with characteristic marks in rolling direction [8]. Scuffing is initiated by heat dissipation in the slide-roll contact under the influence of friction [8–10]. Scuffing preferably occurs at contact points with positive slip of the driving pinion, which are located at the tooth tip. The counterparts can be found at the tooth root of the driven wheel (red highlighted mesh positions in Fig. 1). For high contact ratio gears it has also been experimentally proven that scuffing occurs in flank areas with negative slip [5, 11, 12].

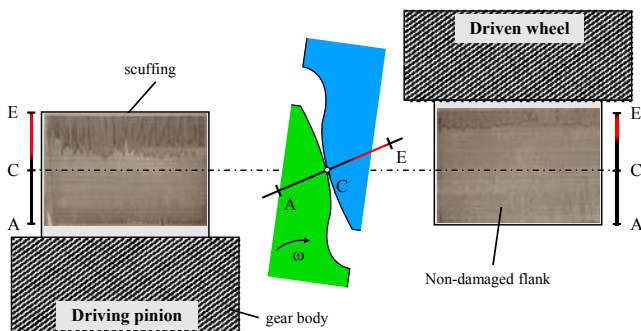


Fig. 1 Scuffing of cylindrical gear pairs

The flash temperature method according to Blok [9, 13] has become established as an indicator for scuffing. It is used in the most reputable standards ISO 6336-20 [14] and AGMA 925-A03 [15]. Flash temperatures describe the frictional energy input into the material near the surface below the contact area in the form of a temperature rise. On a macroscopic scale the temperature field extends up to $0.1 \cdot b_H$ into the material depth related to the Hertzian contact width b_H [16]. The maximum temperature is located close to

the surface. As an alternative indicator for scuffing, energy criteria are suitable [5, 17]. These criteria additionally consider the local contact time and representing the absorption of thermal energy into the contact points.

2.2 High contact ratio gears

To minimize manufacturing costs for gear hobbing, uniform rack profiles have become established in gear production [2]. Standard rack profiles according to ISO 53 [18] result in a contact ratio of $\epsilon_\alpha = 1.4 - 1.6$. In view of increasing flexibility in production, it is becoming more and more common to deviate from these standard profiles and design the gear geometry to meet the load condition as required. The dynamic of drive trains is becoming increasingly important, which is why high contact ratio gears with better stiffness properties are used.

High contact ratio gears ($\epsilon_\alpha = 2.0$) imply the utilization of a larger effective range of the theoretical involute (T_1 to T_2). The resulting gain in contact ratio has a positive effect on the load distribution, but also leads to greater distances between the root or tip mesh positions to the pitch point. Thus, the gear mesh is affected by greater sliding velocities, which leads to a specifically greater dissipation of frictional heat and higher flash temperatures (Fig. 2). From a design point of view, the scuffing load capacity of high contact ratio gears can be addressed with suitable profile modifications by relieving the highly loaded contact points close to the edge of the path of contact.

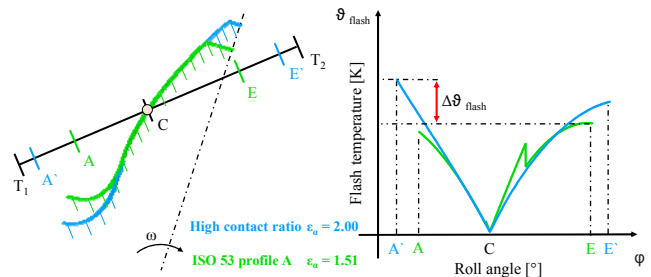


Fig. 2 Influence of the tooth height on the local scuffing loads

3. Methodology

3.1 Experiments

The experiments shown in this paper were carried out on a high-speed gear test for investigating the load carrying capacity of cylindrical gears with pitch line velocities up to $v_u = 100$ m/s. The basic operating principle consists of a back-to-back arrangement of two gearboxes of equal transmission ratios in a closed power loop. The operating principle corresponds to the same as used in conventional gear test rigs according to DIN ISO 14635 [19] but is designed to cover higher speeds.

Fig. 2 shows the schematic layout of the high-speed test rig. In the test gearbox, the test wheelset (2) is thermally insulated by an insulating housing (3). The test gears are injection-lubricated (1) and separated of the bearings without mixing of the lubricating oil circuits. The closed power loop (4) between the test and slave

gearboxes is loaded with torque by a mechanism integrated in the slave wheelset (6). Passing a rotary transmission (8), an axial force is hydraulically applied to the axially shiftable slave wheels (7), resulting in a torque load due to the helix angle. The slave pinions are joint stiff to their shaft. Torque and speed are measured with a torque measuring flange (5). An electric motor (9) feeds in the necessary drive power to maintain the power circuit. **Tab. 1** displays the technical specifications.

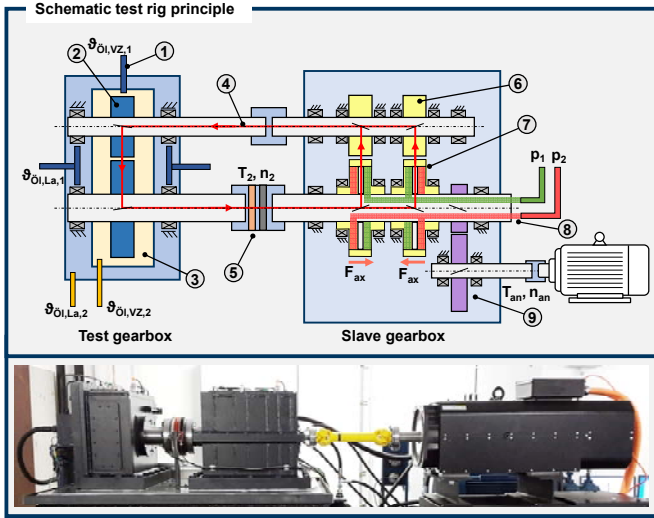


Fig. 3 Schematic principle of the high-speed test rig (HDP)

Tab. 1: Technical specifications of the high-speed test rig (HDP)

Denomination	Symbol	Unit	Value
Centre distance	a	mm	203.3
Rotational speed pinion shaft	n_1	rpm	up to 12000
Torque load at wheel shaft	T_2	Nm	up to 4000
Circulating mechanical power	P_{mech}	kW	up to 3300
Lubricant temperature	ϑ_{oil}	°C	up to 120

For testing purpose, two gear variants (Variant 1 and Variant 2) with a high contact ratio were used. Both variants differ in their maximum sliding speed due to the choice of the normal module. The profile shift coefficients were designed by balancing the specific sliding velocities at the tip and root mesh positions. Each geometry variant covers two sub-variants of profile modifications. The modification-variant A represents a geometry without a profile modification. For modification-variant B, a tip relief was applied in each case. In terms of materials, the test wheels were made of 18CrNiMo7-6 with a conventional case hardening. After profile grinding, the surface roughness in profile direction was $R_a = 0.3 \mu m$ (Tab. 2).

Tab. 2: Test gear geometry

Denomination	Symbol	Unit	Variant 1	Variant 2
Normal module	m_n	mm	4.50	5.50
Number of teeth	z_1 / z_2	-	36 / 54	30 / 45
Face width	b_1 / b_2	mm	22 / 20	22 / 20
Normal pressure angle	α_n	°	20.00	20.00
Helix angle	β	°	5.00	5.00
Profile shift coefficient	x_1 / x_2	-	0.141 / -0.135	-0.060 / -0.568
Tip circle diameter	d_{a1} / d_{a2}	mm	174.63 / 253.45	176.69 / 253.94
Profile modification	Modification		A	B
	C_{a1} / C_{a2}	μm	0.0 / 22.5	0.0 / 27.5
	l_{Ca1} / l_{Ca2}	mm	0.0 / 6.75	0.0 / 8.25
			0.0	0.0

The test conditions were based on the methodology of the scuffing test acc. to DIN 14635-1 [19] (Tab. 3). Operating speeds were varied as part of the project. The torque levels are chosen to

correspond with the Hertzian pressure in pitch point. In each load stage, the test gears are loaded for 15 minutes until constant temperature conditions are established. After completion, the flanks are optically inspected for damage and the torque load is increased until the test gears meet the failure criterion described in [19]. To supply lubricant at increased operational speeds, injection lubrication was installed. In the experiments plain mineral oil of viscosity grade ISO VG 68 was used. The lubricant temperature was set to 90 °C.

Tab. 3: Test conditions

Denomination	Symbol	Unit	Variant 1	Variant 2
Pitch line velocity	v_u	m/s	20 to 70	20 to 55
Hertzian stress (pitch point)	p_{HC}	MPa	146 to 1841 (12 load stages S_{SKS})	146 to 1841 (12 load stages S_{SKS})
Test duration	-	min	15	15
Lubricant temperature	ϑ_{oil}	°C	90	90
Lubricant	-	-	ISO VG 68 (plain mineral oil)	ISO VG 68 (plain mineral oil)

3.2 Simulation

For the modeling of the loaded gear contacts, a load distribution approach by Walkowiak [20] is used. By taking into account material stiffnesses, the local load and velocity parameters between the start and the end of the contact path can be calculated. This approach also allows to consider profile modifications with respect to local load situations in the outer mesh positions. Based on the local load parameters and the EHL-condition, coefficients of friction are calculated using a model by Löpenhaus [21] (Eq. 1).

$$\mu_r = e_1 \cdot v_s^{e_2} \cdot \exp(e_3 \cdot p_H) \cdot (e_4 \cdot \eta_{oil}^2 + e_5 \cdot \eta_{oil} + e_6) \cdots \cdot Ra^{e_7} \cdot \frac{|sl|}{(|sl| + e_8)^2 + e_9} \cdot \rho_{red}^{0.2} \cdot X_L \cdot X_{OS} \quad (1)$$

The estimation of scuffing is done by evaluating friction-sensitive load parameters as the flash temperature or the specific contact energy. For calculating local contact temperatures near the surface, a thermal FD-network is used covering a depth of $m_n/50$. The trajectory of the heat source along the involute causes a heat flux to diffuse into the material through the Hertzian contact patterns. Beyond the model approach by Blok, the thermal network can represent temperature-increasing effects due to the meshing kinematic in the outer mesh positions. According to Joop [5], the time-related energy absorption in the Hertzian contact patterns, specific contact energy (Eq. 2), is suitable as a model approach for the local scuffing load capacity. The general modeling approach is schematically shown in Fig. 4. Further information can be found in [5].

$$E_K = \frac{1}{A_K} \cdot \int_{t_K} \gamma \cdot \mu_r \cdot F_N \cdot |v_g| dt \quad (2)$$

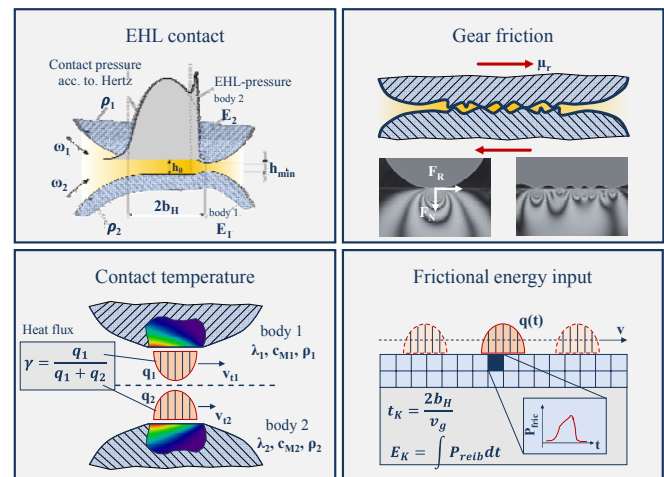


Fig. 4 Simulation approach to estimate scuffing

4. Experimental results

The experimental results in **Fig. 5** show that the tooth height influences the scuffing load capacity negatively. A larger tooth height leads to increased relative sliding velocities. In the test points the failure load stage is reduced by approx. 1 – 2 load levels S_{SKS} . In each individual test condition, the profile modification has a positive effect on the load capacity compared to the unmodified reference. Further information on the determination of the failure load stages depending on the damage pattern can be found in [11, 22]. An analysis of the pitch line velocity on the scuffing load capacity can be found in [5, 12].

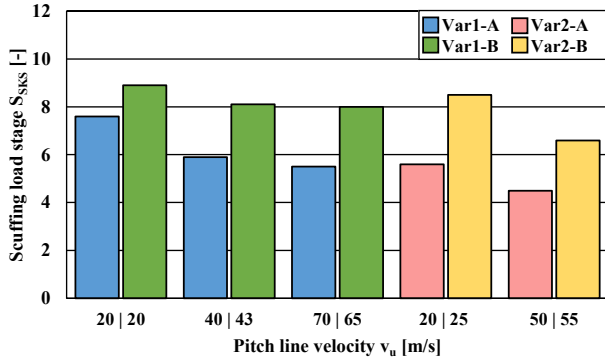


Fig. 5 Scuffing load capacity of the test points

Fig. 6 shows a picture of a scuffed pinion flank after the test. The damage pattern is present uniformly along the flank line. In tangential direction the scuffing marks extend from the outer mesh positions close to the pitch point. SEM images of the local damage points confirm the material welding. The welded contact points are torn apart by the meshing kinematics and a worn and fractured surface with an accumulation of small pores appears. In the non-damaged areas, the grinding grooves of the profile grinding process retain.

5. Transfer of the evaluation method

From the experimental results, it is evident that the scuffing-sensitive design of gears with high contact ratio can be compensated by an adequate profile modification. Scuffing is initiated at the outer mesh positions due to overextending the local load carrying capacity. For improving the load carrying capacity the dissipation of frictional heat in these points must be reduced. The simulation

model presented allows to calculate the local loads and the influence of the profile modification. The dissipation of frictional heat is mainly dependent on the local tribological load condition of normal force, sliding speed, coefficient of friction and the EHL conditions. In addition, effects such as the stiffness-related extension of the contact time and the engagement kinematics in the outer mesh positions have an impact on scuffing. Using profile modifications, mainly the load distribution can be modified. The sliding velocities, curvatures and the influence on the coefficient of friction are less dependent of the profile modification.

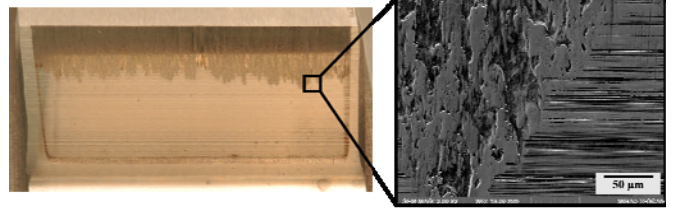


Fig. 6 Picture of a scuffed gear flank with a close-up SEM image

To evaluate the scuffing load capacity of various profile modifications, **Fig. 7** shows the local load distribution in form of the contact pressure (a) and the normal force (b), the specific contact energy (c) and the contact temperatures (d) along the path of contact. The path of contact is represented by the involute radius of the driving pinion to indicate the damage location and the effects during the outer meshing positions. For the simulation the basic geometry is identical to variant A. The variants without or less tip relief (variants $C_{a1} = 0 \mu\text{m}$ to $C_{a1} = 40 \mu\text{m}$) exhibit large normal forces in the outer meshing positions as well as double rollovers of individuals points, which leads to locally high contact temperatures and frictional loads. On the other hand, the area around the pitch point is less heavily loaded. As the amount of tip relief increases, the normal force is concentrated in the region around the pitch point, which leads to reduced load of the outer mesh positions. The almost linear increase in the contact normal force of the variant $C_{a1} = 80 \mu\text{m}$ is desirable here. Lowering the normal forces, results in the scuff-sensitive flank points being relieved in terms of their temperature development. The scuffing load carrying capacity significantly benefits from the profile modified involute. However, the load capacity regarding pitting can decrease due to the higher contact pressure around the pitch point. Ultimately, these two types of stress must be weighed up against each other.

In the design process of profile modifications, it is important to

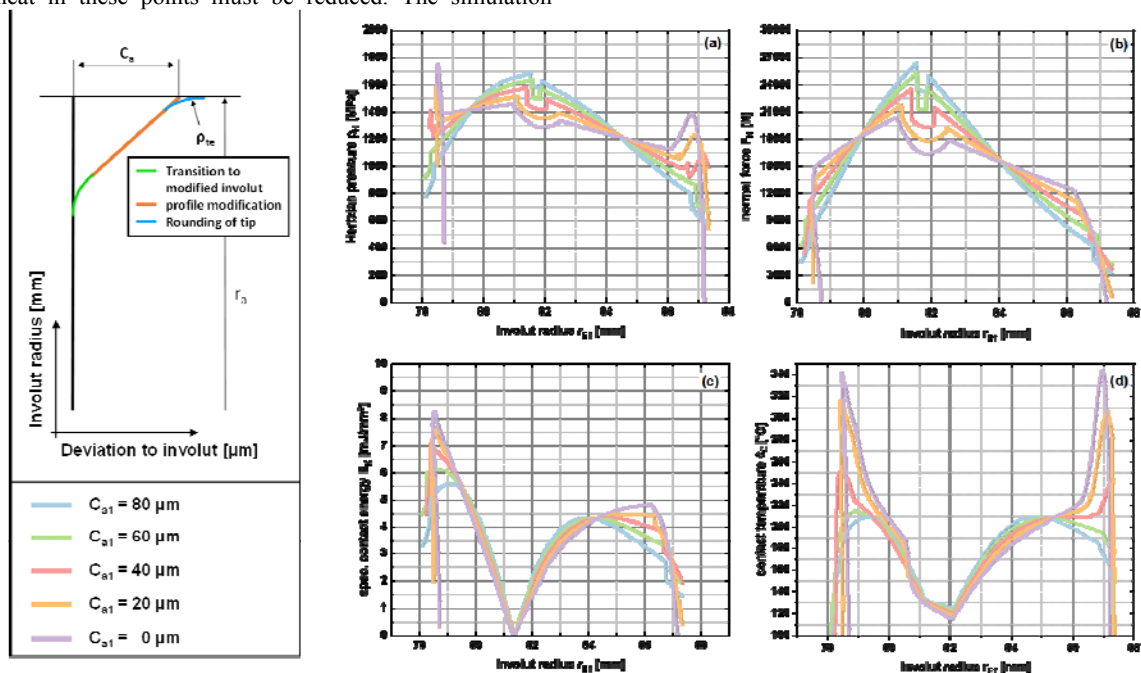


Fig. 7 Analysis of different profile modifications on the scuffing load carrying capacity

compensate for elastic tooth deformation so that double rollovers and impulse-like initial engagements do not occur in the outer mesh positions. As a design suggestion, the following strategy can be recommended for high contact ratio gears:

1. The tip relief must fully compensate for the elastic deformation of the tooth pair. Due to the larger tooth height, $C_{a1} = m_n/100$ as an approximate value for the tip relief is recommended to compensate for high loads. The shape of the profile modification (linear, progressive) can be used to improve the actual contact ratio of the lower loaded gear contact. Transition functions between the non-modified involute, the modified involute and the tip rounding also lead to better curvature conditions.
2. The length of the profile modification must be applied so that a smooth load gain during the gear mesh is achieved. In the case of high contact ratio gears, the profile modification extends close to the pitch point.
3. The modification of the flank line relieves the edges of the gear width and compensates for torsional deformations.

6. Discussion

In this article, the influences of high contact ratio gears on their scuffing load capacity are shown. Due to their large tooth height, high contact ratio gears can be more sensitive to scuffing if the profile is not sufficiently modified. In the gear design, it is important to reduce the load in outer mesh positions and thus the dissipation of frictional heat. In the experiments, an increased scuffing load capacity of gears with a tip relief could be determined compared to non-modified gears. Recommendations on the design of profile modifications could be derived based on a simulation model.

The experiments shown were all carried out with plain mineral oil and profile-ground gears. In modern gear applications, cylindrical gears with enhanced surface conditions are increasingly used. In addition, the load-carrying capacity of lubricants can be significantly increased by the addition of additives. In the moderate pitch line velocity range, these effects have already been confirmed experimentally. For the high-speed applications, there is still a need for research to determine whether these improvements in load carrying capacity also hold at higher speeds and under improved EHL-conditions.

7. References

- [1] DIN 3979, *Zahnschäden an Zahnradgetrieben*, (1979)
- [2] G. Niemann, H. Winter, *Getriebe allgemein, Zahnradgetriebe - Grundlagen, Stirnradgetriebe*, 2. Auflage (2003)
- [3] H. Linke, *Stirnradverzahnung: [Berechnung - Werkstoffe - Fertigung]*, 2. Auflage (2010)
- [4] P. Hepermann, *Untersuchungen zur Fresstragfähigkeit von Groß-, Schräg- und Hochverzahnungen*, PhD-thesis Ruhr-Universität Bochum (2013)
- [5] M. Joop, *Die Fresstragfähigkeit von Stirnrädern bei hohen Umfangsgeschwindigkeiten bis 100 m/s*, PhD-thesis Ruhr-Universität Bochum (2018)
- [6] R. W. Snidle, H. P. Evans, *Understanding Scuffing and Micropitting of Gears* (2004)
- [7] K. Sommer, R. Heinz, *Verschleiß metallischer Werkstoffe*, 2. Auflage (2014)
- [8] K. Michaelis, *Die Integraltemperatur zur Beurteilung der Fresstragfähigkeit von Zahnradgetrieben*, PhD-thesis Technische Universität München (1987)
- [9] H. Blok, *Theoretical study of temperature rise at surfaces of actual contact under oiliness lubricating conditions*, Proc. Gen. Disc. Lubric. 2, p. 222–235 (1937)
- [10] G. Lechner, *Die Freblastgrenze bei Stirnrädern aus Stahl*, PhD-thesis Technische Universität München (1966)
- [11] M. Joop, H. Ittenson, *Örtliche Fresstragfähigkeit. Abschlussbericht zu Forschungsvorhaben FVA 598 II* (2018)
- [12] J. Vorgerd, P. Tenberge, *Scuffing of cylindrical gears with pitch line velocities up to 100 m/s*, Forschung im Ingenieurwesen, Jg. 2 (2021)
- [13] H. Blok, *Measurement of temperature flashes on gear teeth under extreme pressure conditions*, Proc. Gen. Disc. Lubric. 2, p. 14–20 (1937)
- [14] ISO 6336-20, *Calculation of load capacity of spur and helical gears - Part 20: Calculation of scuffing load - Flash temperature method* (2017)
- [15] AGMA 925-A03, *Effect of Lubrication on Gear Surface Distress* (2003)
- [16] J.C. Jaeger, H.S. Carslaw, *Conduction of heat in solids*, 2. Edition (1959)
- [17] J.O. Almen, *Surface Deterioration of Gear Teeth*, Conference on Mechanical Wear (1948)
- [18] ISO 53, *Stirnräder für den allgemeinen und Schwermaschinenbau - Standard-Bezugszahnstangen - Zahnprofile*, (1998)
- [19] DIN ISO 14635, *FZG-Prüfverfahren Teil 1 - FZG-Prüfverfahren A/8,3/90 zur Bestimmung der relativen Fresstragfähigkeit von Schmierölen*, (2006)
- [20] M. Walkowiak, *Örtliche Belastungen und Verschleißsimulation in den Zahneingriffen profilkorrigierter gerad- und schrägverzahnter Stirnräder zwischen Einfederungsbeginn und Ausfederungsende*, PhD-thesis Ruhr-Universität Bochum (2013)
- [21] C. Löpenhaus, *Untersuchung und Berechnung der Wälzfestigkeit im Scheiben- und Zahnflankenkontakt*, PhD-thesis RWTH Aachen (2015)
- [22] L. Schlenk, *Untersuchungen zur Fresstragfähigkeit von Großzahnradern*, PhD-thesis Technische Universität München (1995)

Abbreviations

a	[mm]	Center distance
b	[mm]	Facewidth
b _H	[mm]	Half Hertzian contact width
c _m	[J/kg□K]	heat capacity
d _a	[mm]	Tip circle diameter
e	[-]	Weight parameters
h ₀	[μm]	Central EHL fluid film thickness
h _{min}	[μm]	Minimum EHL fluid film thickness
l _{Ca}	[mm]	Length of tip relief
m _n	[mm]	Normal modulus
n ₁	[rpm]	Rotational speed
p _H	[MPa]	Hertzian stress
q	[W]	Frictional heat
r _E	[mm]	Involute radius
sl	[-]	Slide-roll ratio (slip)
t _K	[s]	Local contact time
x	[-]	Profile shift coefficient
z	[-]	Number of teeth
v _g	[m/s]	Sliding velocity
v _u	[m/s]	Tangential velocity (pitch point)
v _Σ	[m/s]	Sum velocity
A	[-]	Engagement point of active root circle
A _K	[mm ²]	Hertzian contact pattern
C	[-]	Engagement point of pitch circle
C _a	[μm]	Tip relief

E	[-], [GPa]	Engagement point of tip circle, Modulus of elasticity
E_K	[mJ/mm ²]	Specific contact energy
F_N	[N]	Normal Force
F_R	[N]	Friction Force
P_{fric}	[W]	Frictional heat
P_{mech}	[W]	Mechanical power
R_a	[μm]	Arith. mean roughness
S_{SKS}	[-]	Failure load Stage
T	[-], [Nm]	Tangent point, Torque
X_L	[-]	Lubricant factor
X_{OS}	[-]	Surface factor
α	[°]	Normal pressure angle
β	[°]	Helix angle
γ	[-]	Heat sharing factor
ε_a	[-]	Contact ratio
η_{oil}	[mPas]	Dynamic viscosity
λ	[-]	Specific fluid film thickness
μ_r	[-]	Coefficient of friction
ρ_{red}	[mm]	Radius of curvature
ϑ_{flash}	[K]	Flash temperature
ϑ_{oil}	[°C]	Oil temperature
ϑ_C	[°C]	Contact temperature
Indizes		
1,2	Pinion / wheel	

LNG fueled ship type "C" storage tank pressure rise particularities related to the bunkering flow

Delyan Hristov

Nikola Vaptsarov Naval Academy - Varna, Bulgaria
d.hristov@nvna.eu¹, d.hristov@naval-acad.bg¹

Abstract: In the proposed publication it is conducted simulation-based experiment with the bunkering process of type "C" LNG containing tank. According to the specific features of the LNG bunkering process it is analysed the nature of the boiling off mechanism of the cryogenic fluid during bunkering transfer. The attained data by the experiment is analysed including the specific condition of heat ingress simulation. On the base of the results there are stated conclusions and recommendations to the ship operators related to the limiting conditions of the pressure vessels operation as it is the type "C" tank.

Keywords: LNG AS MARINE FUEL, TYPE C BUNKERING TANK, BUNKERING FLOW, TANK PRESSURE RISE, HEAT INGRESS TO TANK

1. Introduction

The new generation ships with reduced CO₂ emissions as part of the IMO strategy for the reduction of the greenhouse gas emissions from ships nowadays force the development of various technologies [1, 2, 4, 5, 7, 14] to scope with the problem, but mostly rely on liquified natural gas (LNG) as fuel. The specifics of the LNG handling but are not well known by the majority of the seafarers and this led to great concern about the safety of the growing number of gas fueled ships which are not gas tankers as their purpose. There are a number of issues related to the specifics of handling the LNG as a cryogenic liquid able to evaporate, expand and burn shortly after it is accounted loss of containment of a pipeline or tank holding the same. The hazards of the LNG are with direct effect on the human health and need to be minimized as reasonable as possible to not allow uncontrolled spillage of LNG due to loss of containment.

In this publication it will be considered the bunkering process related with LNG extensive evaporation and the problem with handling it to safe state so it could not exceed the safety margins of the pressure release valves or the material strength of the system.

The aim in the publication is to provide proper guide to the operators about the tank pressure changes during bunkering, related to the flow of the LNG transferred, thus facilitating the training process on the new topics related to the gas handling [8, 10]. The tasks linked to the aim accomplishment will be to perform a planned experiment with various transfer rates on a type C holding tank while there are similar surrounding conditions so to evaluate the influence of the rate of the transfer and the boil-off rate of the LNG which in turn would rise the pressure in the tank.

In the case of usage of type C tanks, the pressure rise can be allowed to reach higher limits compared to the other types of tanks with close to atmospheric operating pressure, but on the final stage with limited free volume of the tank the pressure could rapidly change its value, so to pass the higher limit.

2. The type C tank and the LNG system

In the publication the object under evaluation is type C double shell LNG tank with as shown on Fig.1 with total capacity of 130 m³. These types of tanks are commonly used on small scale ships with average power outputs and short range of service [16], so to be able frequently to be refueled. Such kind of pressure vessels but with larger scales up to 1300 m³ or similar volumes could be seen on large ocean-going vessels as bulk carriers, car carriers, tanker vessels.

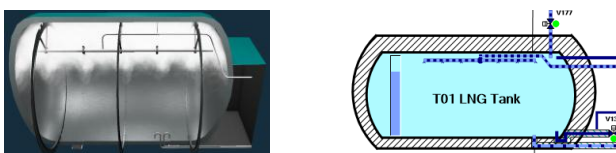


Fig. 1 LNG tank type C double shell vacuum insulated [15]

The specifics in the operation of this kind of LNG tanks is related to their ability to handle higher pressures than the other type of LNG tanks, but with restricted volumes available due to the specifics of the shapes of the pressure vessels as they are. On the end of the filling process of such a tank, the restricted free volume rapidly changes the condition of the gases on top of the liquid to high rate of pressure rise. As during the bunkering, the liquid flowing through the bunkering line receives heat from the surrounding area (see Fig. 2) it is considered an intensive evaporation rate [12] which need to be evaluated.

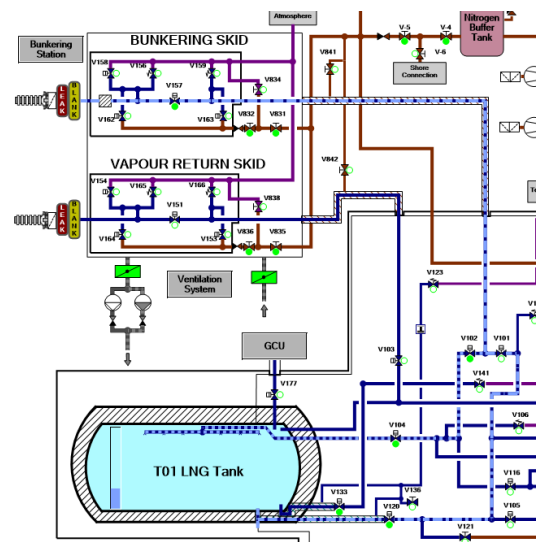


Fig. 2 Bunkering system and bunkering tank [15].

3. The experiment with the bunkering flow

It is considered the bunkering experiment to be carried out at a simulated environment as it is the LNG Pac simulator of Wärtsilä[15]. The simulation allows to be carried out different scenarios with flexible parameters in an acceptable authenticity if the simulation model [6, 9, 11] is closely matching with the real object. These can be performed with real systems in an expensive and complicated manner [3]. In the case of the LNG Pac simulation there are several authorities confirming the realistic and comprehensive features of the model facing the requirements of the classification societies to serve as proper model of the real LNG Pac system.

The simulated experiment allows to be performed critical operations with marginal parameters [13, 17, 18] while no safety issues and additional risks may occur in the real environment and this advantage is used to reproduce the different flow of the bunkering transfer up to the filling limit of the tank on every attempt. The other advantage is that we have ready empty tank in

every consecutive start of the simulation process from same initial condition.

For the experiment the tank was filled with minimal amount of liquid LNG, so to be sufficiently cooled down with no additional resistance in the bunkering system. The vapor return manifold has been operated with same back pressure. Several bunkering transfers were carried out with different flows through the bottom filling line and the pressure development was registered at a specific level of 25, 50, 75 and 95 % filling of the tank. Same scenario was repeated with simulated heat ingress to the tank as 25% of compromised insulation efficiency, which may be considered the realistic limit of the insulation deterioration during the entire service of the system with normal wear rate. The approach with the heat ingress was intended to evaluate the influence of the tank maturity and the normal wear process to the daily routines while bunkering on the end of service life of the ship. The results obtained are shown in table 1.

Table 1: Results obtained by the experiment

Tank filling capacity [%]	Bunkering flow 50 m ³ /h	Bunkering flow 100 m ³ /h	Bunkering flow 150 m ³ /h
	LNG Tank Press. [bar]	LNG Tank Press. [bar]	LNG Tank Press. [bar]
25	1.7	1.79	1.78
50	1.81	2.01	2.09
75	2.11	2.57	2.78
95	3.46	5.09	6.77
Bunkering process with heat ingress 25%			
Tank filling capacity [%]	Bunkering flow 50 m ³ /h	Bunkering flow 100 m ³ /h	Bunkering flow 150 m ³ /h
	LNG Tank Press. [bar]	LNG Tank Press. [bar]	LNG Tank Press. [bar]
25	1.72	1.76	1.86
50	1.84	2.02	2.12
75	2.15	2.59	2.89
95	3.63	5.14	6.63

4. Experiment data analysis

The data attained was processed at MS office tool as figures and trending lines were acquired. The data for the plain experiment is shown of Fig. 3

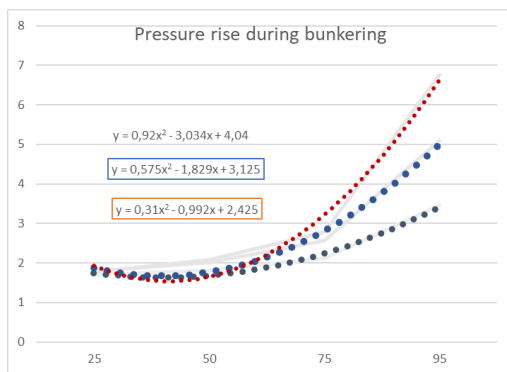


Fig. 3 Pressure rise in the tank with different flow of the bunkering.

The regression models attained by the analysis show close matching with the real process in a polynomial mathematical model of 3rd order. The three modes of the bunkering flow led to different pressure rise on the second half of the tank filling which is related to the reducing free volume of the half of the cylinder as it is the shape of the tank. At the same time the boil-off rate is increasing with the rise of the flow due to the intensified mixing of the liquid in the tank thus increasing the internal friction in the liquid.

The pressure difference between the lowest considered flow and the highest one is around 3 bar. It can be expressed that in case of

even higher flow than the performed the pressure could overcome the opening pressure of the relieve valve.

The experiment repeated with heat ingress to the tank gave results as per the Fig.4, where slight deviations with the normal condition of the tank are encountered.

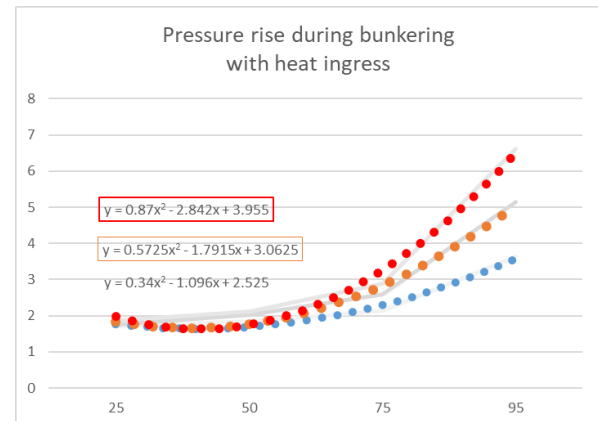


Fig. 4 Pressure rise in the tank with different flow of the bunkering with heat ingress to the tank

The polynomial equations of the both experiments compared show slight differences between the normal technical condition and the condition with insulation impaired:

$$y = 0,92x^2 - 3,034x + 4,04 \quad (1)$$

$$y = 0,87x^2 - 2,842x + 3,955 \quad (2)$$

Equation (1) and (2) express the pressure rise on flow 150 m³/h. Both show similar mathematical type and close value of the coefficients on the variables. Same is for the equations for the flow on 100 m³/h, (3) for normal condition and (4) for the heat ingress condition:

$$y = 0,575x^2 - 1,829x + 3,125 \quad (3)$$

$$y = 0,5725x^2 - 1,7915x + 3,0625 \quad (4).$$

The equations for the curves for 50 m³/h flow show similarity as with the other flows and close behavior on both cases (5) for normal condition and (6) for deteriorated condition:

$$y = 0,31x^2 - 0,992x + 2,425 \quad (5)$$

$$y = 0,34x^2 - 1,096x + 2,525 \quad (6).$$

The obtained lines for both scenarios are shown simultaneously on Fig.5.

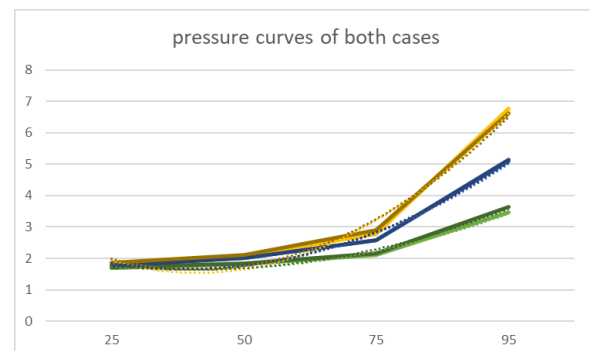


Fig. 5 Pressure rise in the tank compared on normal and deteriorated condition

5. Conclusions

According to the experiment results analysis they can be stated the following conclusions:

- The bunker flow rise lead to increased pressure in the tank of the bunkering completion due to the increased boil-off rates.
- With bunker flow adjustment it is possible to reduce the pressure in respect to the limiting conditions during bunkering. Proper bunkering flow management will act as a countermeasure on the bunker tank pressure rise.
- The influence of the heat ingress in the lower extend gives low impact on the pressure rise. This lead to the following conclusion that the insulation maturity of the tank will not change the tank behavior during bunkering processes significantly during the extend of its operating life.

6. Acknowledgements

The extend of the experiment carried out reaches a specific single procedure of bunkering an LNG tank through bottom filling line and may be seen some differences in other approaches.

The experiment is carried out in Nikola Vaptsarov Naval Academy simulator of LNG bunkering system on the available models reproducing real objects with the extend of the simulation capabilities.

The conclusions stated may not be in force for larger tanks with larger surfaces which can be seen on larger ocean-going vessels. For proper evaluation of the similar processes with such tanks there must be conducted additional experiments.

The aim in the publication is achieved, to express the pressure dependence on the bunkering transfer flow as the influence of the heat ingress to the tank.

7. References

1. D Popov, *Investigation of the influence of diesel fuels (standard diesel fuel and standard diesel fuel after treatment with ANSTOTECH device) on specific fuel oil consumption of marine diesel engine type SKL 3NVD24, XVIII International scientific congress MACHINES. TECHNOLOGIES. MATERIALS, YEAR IV, ISSUE 1 (18)*, pp 31-34, Borovets, Bulgaria (2021), ISSN 2535-003X (ONLINE).
2. I. Bakalov; D Popov, *Investigation of the influence of diesel fuels (standard diesel fuel and standard diesel fuel after treatment with ANSTOTECH device) on the average temperature of marine diesel engine type SKL 3NVD24, XVIII International scientific congress MACHINES. TECHNOLOGIES. MATERIALS, YEAR IV, ISSUE 1 (18)*, pp 34 -38, Borovets, Bulgaria (2021), ISSN 2535-003X (ONLINE).
3. D. Vasilev; H. Hristov; G. Lyutskanov, *Working Parameters of a DP Vessel Power Plant. First International Marine Engineering Conference*, Varna, (2018), pp. 180-186. ISBN 978-619-7428-31-5.
4. H. Hristov; I. Bakalov; B. Shopov; D. Yovkov, *Modeling of the dependence of the produced amount of hydrogen gas (y) on the amperage of cell (x) of a marine diesel engine SKL 3NVD24. Pedagogika-Pedagogy, Volume 93, Number 6s, (2021)* (<https://doi.org/10.53656/ped21-6s.24mod>).
5. H. Hristov; I. Bakalov; B. Shopov; D. Yovkov, *Modeling of the dependence of CO2 contained in the exhaust gases on the amount of hydrogen gas supplied to the engine. Pedagogika-Pedagogy, Volume 93, Number 6s, (2021)* (<https://doi.org/10.53656/ped21-6s.24mod>).
6. H. Hristov; J. Moskov, *Application of mathematical models for evaluating the consequences of damages on crankshaft of slow speed marine diesel engine, Морски научен форум*, стр. 69-73, ББМУ „Н. Й. Вапцаров“, (2016), ISSN: 1310-9278.
7. K. Nedev, *An investigation of control system for ship cleaning equipment, First International Marine Engineering Conference*, Engineering Faculty Nikola Vaptsarov Naval Academy, Varna, (2018), pp. 141-147. ISBN 978-619-7428-31-5.
8. M. Vasilev, *New challenges against instructors for marine engineers, Trans&Motauto* (2015), Varna
9. M. Vasilev, *Usage of FESTO simulator for marine systems, Trans&Motauto* (2015), Varna
10. Se-Hyun Han; Yong-Sup Yun; Jong-Su Kim; Young-Chan Lee, *A Study on the Development of Educational Programs for LNG Bunkering in Consideration of the Safety System, Journal of the Korean Society of Marine Environment & Safety Research Paper Vol. 22, No. 3*, pp. 268-277, May 31, (2016), ISSN 1229-3431(Print) / ISSN 2287-3341(Online)
11. W. Cheng; J Yonglin, *Modeling, simulation and analysis of tank thermodynamic behaviors during no-vent LNG bunkering operations, Cryogenics, Volume 120*, (December 2021)
12. Yude Shao; Yoon-Hyeok Lee; You-Taek Kim; Ho-Keun Kang, *Parametric Investigation of BOG Generation for Ship-to-Ship LNG Bunkering, Journal of the Korean Society of Marine Environment & Safety, Vol. 24, No. 3*, pp. 352-359, May 31, 2018, ISSN 1229-3431(Print) / ISSN 2287-3341(Online)
13. И. Бакалов, *Използване на симулационен комплекс за провеждане на обучение и тренировки по борба с пожари Морски научен форум, том 2*, Варна (2016)
14. И. Бакалов, Р. Бакалова, *Използване на алтернативни горива в корабните дизелови двигатели, икономически фактор. Шумен, Конференция с международно участие "MATTEX 2014"*. ISSN: 1314-3921 стр. 228 - стр. 232
15. Wärtsilä LNG Bunkering and Fuel Gas Supply System Simulator
16. ABS, *LNG Bunkering: Technical and Operational Advisory*, (2021)
17. Г. Димитров; Й Сивков, *Съвременните технологии в бъдещето на плавателния състав Варненски медицински форум, т. 6, бр. 2*, 2017 с.152-155
18. Г. Димиров, *Интелигентни приложения за оценка на риска по време на корабна маневра, Заключителна конференция „Наука в служба на обществото – 2014“ сп.„Известия“ – стр.117-123 Съюз на учените Варна 2014г.* ISSN 1314-3379

Optimal length of a railway curve for a given design speed

Matey Iliev

University of Architecture, Civil Engineering and Geodesy

Ph.D student, Railways dept.

matey_iliev@outlook.com

Abstract: The majority of railway projects in our country aim at the maximum utilization of existing railway infrastructure, increase of the operation parameters, frequently at the condition of achieving interoperability. Increasing permissible speeds of trains invariably requires increasing the radii and lengths of curves. However, at small delta angles the use of the minimum design speed radius gives suboptimal results in terms of the total length of the curve. The report presents a parametric method for optimizing the railway curves at small delta angles in view of the necessity of achieving higher speeds on existing lines.

Keywords: RAILWAY ALIGNMENT, RAILWAY CURVE,

1. Introduction. Definition of terms

From the condition of gradual increase and decrease of lateral accelerations, railway curves are designed with a bilinear curvature diagram. Exiting the tangent, a transition curve begins (transition curves with a linear increase in curvature are accepted as the norm) with a length determined by the curvature gradient. This is followed by a circular curve with a constant radius according to the design speed as well as a second transition curve identical to the first one.

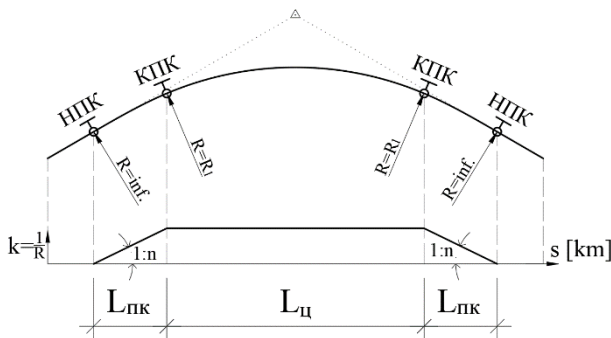


Fig. 1 Curvature diagram of a railway horizontal curve

Prerequisite: All variables in the report are considered with their dimensions according to the SI system (m, s, rad, etc.). In cases where a given variable in an expression has a different dimension from the specified ones, it is marked with a lower index as follows:

$V_{[km/h]}$: To be read as „velocity in km/h“

The main variables to be considered when designing railway curves are: the radius, the design speed, the residual centrifugal acceleration, the cant, the length of the transition curve.

1.1 Radius

The choice of radius R for a curve depends on many factors, thus its value has both a lower and an upper limit. The minimum radius is determined on the basis of not exceeding the permissible centrifugal accelerations when traveling at the design speed. The value of the maximum permissible radius is recommended with the consideration of track maintenance.

1.2 Design speed

Unlike road construction, where a distinction exists between the concepts of "design speed" and "speed of movement", in the field of railway construction the two most often coincide. The design speed $V_{[km/h]}$ is usually a preset parameter. It is defined in accordance with the category of the railway line described in Chapter Two of [1]. Apart from the national categorization, in projects with European co-financing, subject to certification for interoperability, the European classification, defined in Regulation 1299/2014 [2], is also applicable in our country [3]. While for category III railways, the design speed may be below 80 km/h, for category II railways it is in the range of 80-100-130 km/h, and for railways and routes

included in the TEN-T network design speeds reach as much as 160 km/h.

For the purposes of this report, it is assumed that the speed is a predefined parameter of the movement.

1.3 Centrifugal acceleration

When moving in a horizontal curve with a given speed V , centrifugal acceleration occurs. When tilting the railway track in the direction of turning, the projection of the acceleration of gravity in the track plane is non-zero (centripetal acceleration) and its direction is opposite to the projection of the centrifugal acceleration. This effect is called *reducing centrifugal acceleration*.

The resulting acceleration in the track plane, called *residual centrifugal acceleration* is the value that is the subject of norming in our country and which is leading in the choice of radii and cant values in railway curves. Its value is denoted by A_{cf} .

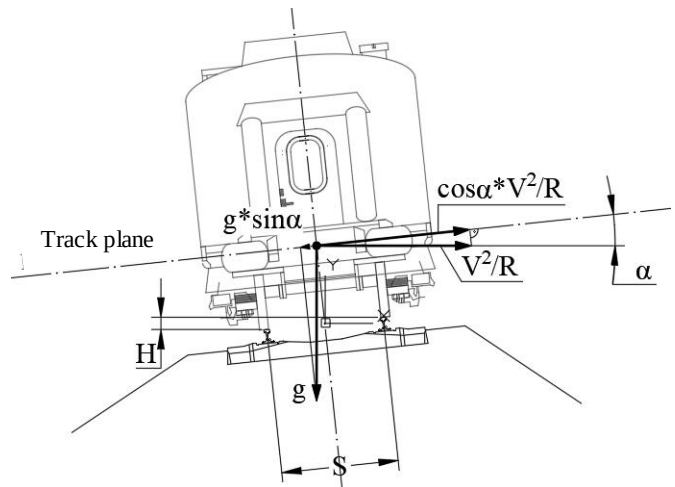


Fig. 2 Reducing centrifugal acceleration

According to the figure above for the angle α

$$\alpha = \tan^{-1} \frac{H}{S}, \quad (1)$$

where H [m] is the cant value (superelevation of the outer rail), S [m] is the distance between rail axes.

The derivation of the expression for the residual centrifugal acceleration is performed under the assumption that the angle α of the above figure is sufficiently small. ($\alpha \leq 6^\circ$), so that $\sin \alpha \approx \tan \alpha$ and $\cos \alpha \approx 1$.

$$A_{cf} = \frac{V^2}{R} \cdot \cos \alpha - g \cdot \sin \alpha \quad (2)$$

$$A_{cf} = \frac{V^2}{R} - g \cdot \tan \alpha \quad (3)$$

$$A_{cf} = \frac{V^2}{R} - g \cdot \frac{H}{S}, \quad (4)$$

where V [m/s] is the design speed, R [m] is the curve radius, g [m/s²] is acceleration of gravity.

In our country the maximum allowable value of A_{cf} is $0,65 \text{ m/s}^2$, and railway curves with normal cant values are designed with A_{cf} values in the range of $0,42\text{-}0,43 \text{ m/s}^2$.

1.4 Cant

The cant is the variable through which the centrifugal acceleration is reduced, as shown by equation (4). Substituting A_{cf} with 0 in equation (4) for the cant is obtained:

$$H = \frac{S \cdot V^2}{g \cdot R} \quad (5)$$

This is called *theoretical cant*: the cant at which traveling with velocity V in a curve with radius R the residual centrifugal acceleration is 0 m/s^2 . To facilitate calculations, it is common to substitute $S = 1,5 \text{ m}$, $g = 9,81 \text{ m/s}^2$, and to shift from $[\text{m/s}]$ to $[\text{km/h}]$:

$$H_{[mm]} = \frac{11,82 \cdot V_{[km/h]}^2}{R} \quad (6)$$

The theoretical cant is not often used in conventional rail, due to the fact that only a part of the trains run at the design speed for the railway line. Instead, when choosing cant value it is accepted to reduce the coefficient of 11.82, taking into account the different speeds of different categories of trains. The *normal cant* is:

$$H_{[mm]} = \frac{8 \cdot V_{[km/h]}^2}{R} \quad (7)$$

Under troubled conditions, the minimum allowable cant is often sought after as the transition ramps for its realization at both ends of the curve are shortened. Substituting A_{cf} with $A_{cf,max} = 0,65 \text{ m/s}^2$ in equation (4) one obtains:

$$H = \frac{S \cdot V^2}{g \cdot R} - A_{cf,max} \cdot \frac{S}{g} = \frac{S \cdot V^2}{g \cdot R} - 0,65 \cdot \frac{S}{g} \quad (8)$$

This is the minimum allowable cant, ie. traveling with the velocity V through a curve with the radius R the residual centrifugal acceleration is $0,65 \text{ m/s}^2$.

1.5 Cant deficiency

The second term in (8) is called *cant deficiency*. This represents the cant that would reduce a given centrifugal acceleration for the given track gauge. It is marked D :

$$D = A_{cf} \cdot \frac{S}{g} \quad (9)$$

For the upper limit $A_{cf} = 0,65 \text{ m/s}^2$, $S = 1,5 \text{ m}$, $g = 9,81 \text{ m/s}^2$ maximum allowable cant deficiency is:

$$D_{max} = 0,65 \cdot \frac{1,5}{9,81} \approx 0,1_{[m]} = 100_{[mm]} \quad (10)$$

It should be noted that there also exists the concept of *cant excess*, but it will not be considered as it is not of interest in this report.

1.6 Length of the transition curve

Transition curves are elements of the track geometry that are located between straight sections and circular curves. The two main functions of transition curves are:

- To ensure the smooth increase of curvature, and with it the smooth increase of centrifugal acceleration
- To accommodate the cant transition and, in some cases, the track gauge widening

In order to achieve uniformity in the curvature and residual centrifugal acceleration diagrams, it is assumed that the transition curve and the cant ramp coincide. Since the cant transition is the section of the railway track with the proven highest risk of derailment [4], the length of the transition curve is determined by the cant to be realized at its end, as well as by the allowable slope of the cant ramp.

Normal, shortened and short transition curves are defined in the legislation in our country. Distinction between them is mainly based on the used slope of the cant ramp. The general expression for determining the length of the transition curve L_{tc} is:

$$L_{tc} = k * H, \quad (11)$$

where k is the cotangent of the ramp slope angle and H [m] is the cant value.

The value of k is determined from the design speed $V_{[km/h]}$, using the following expressions:

$$k = 8 * V_{[km/h]} \quad (12) \quad \text{for short and shortened transitions}$$

$$k = 10 * V_{[km/h]} \quad (13) \quad \text{for normal transitions}$$

In the present report mainly the case with $k = 10 * V_{[km/h]}$ will be considered, as in practice the use of steep cant ramps is avoided if possible.

2. Limitations on the railway curve length

Chapter Five, Section IV of [1] defines the cant ramp, hence the determination of the length of the transition curve. A more detailed description of the methodology and tables in which the lengths are calculated for different conditions can be found in [5].

According to Section VII of [1], the minimum length of a straight section and the minimum length of a circular curve segment is:

$$L_{min} = 0,5 \cdot V_{[km/h]} \quad (14)$$

This condition stems from the necessity for the individual geometric elements of the track geometry to be dynamically independent – when a vehicle enters the next curve, the oscillations due to the movement in the previous one to have been sufficiently damped. Thus, the route of the railway line with its successive curves should not allow resonance occurring in the movement of vehicles. [6]

3. Optimal radius to achieve the minimum length of the curve

From the expressions given in 1.4 for determining the cant it is evident that the radius is in the denominator, ie. as the radius decreases, the required cant increases. At the same time, the expressions in 1.6 show that as the cant increases, so does the required length of the transition curve.

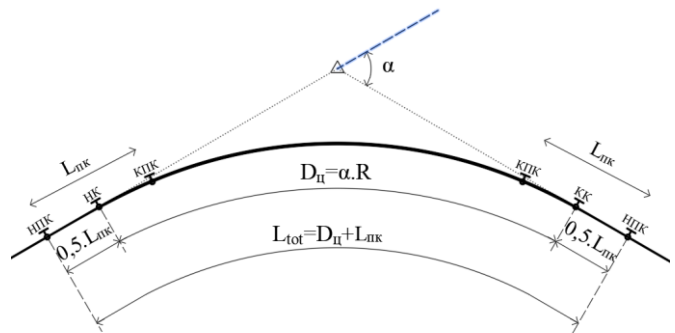


Fig. 3 Transition curves design scheme. Determining the total length of the curve

The transition curve has half its length in the straight and the other half in the circular curve. It should be noted that with the introduction of a transition curve, the circular curve undergoes some displacement and change in its length due to the delta angle of the transition. This effect is ignored in this report. The total length L_{tot} of the curve between the begin transition points, in this case, is:

$$L_{tot} = D_u + 2 * \frac{L_{tc}}{2} = D_u + L_{tc} \quad (15)$$

Where:

$$D_u = \alpha * R \quad (16)$$

$$L_{tc} = 10 * V_{[km/h]} * H_{[m]} = 36 * V_{[m/s]} * H_{[m]} \quad (17)$$

Note: The variable D_u above is not the actual length of the circular curve between the transitions, it is the theoretical length of a circular curve inscribed between the two given tangents.

Due to the increase in the lengths of the transition curves with decreasing the radius, the total length of the curve L_{tot} changes nonlinearly with respect to the radius of the curve. For the sake of clarity, the figure below shows a graph of the change in the length of the curve relative to the radius at $V = 100 \text{ km/h}$ and a delta angle of $\alpha = 5^\circ$:

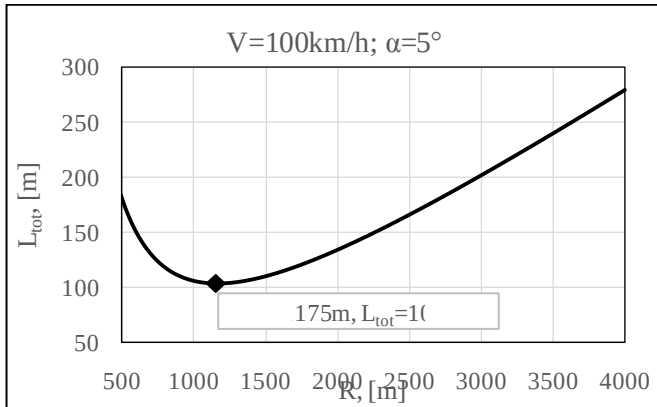


Fig. 4 Total length of the railway curve in relation to a selected radius

Below are the expressions for determining the optimal radius at which the total length of the curve is at a minimum.

Substituting with what is obtained by equation (8):

$$L_{tc} = 36.V * \left(\frac{S.V^2}{g.R} - 0,65 \frac{S}{g} \right) = \frac{36.S.V^3}{g.R} - \frac{36.V.S.A_{cf,max}}{g} \quad (18)$$

By expressing all quantities as a function of radius, delta angle and design speed, one can solve for the optimal radius that minimizes the curve length. This is achieved through differentiating L_{tot} by R:

$$\frac{dL_{tot}}{dR} = \frac{d}{dR} (D_u + L_{tc}) = \alpha - \frac{36.S.V^3}{g.R^2} \quad (19)$$

Note: The first derivative with respect to R of equation (19) is obviously positive – proof that the root of the equation is a local minimum!

Substituting $\frac{dL_{tot}}{dR} = 0$

$$\alpha = \frac{36.S.V^3}{g.R^2} \quad (20)$$

Convert the above expression to find the optimal radius R_{opt} :

$$R_{opt} = \sqrt{\frac{36.S.V^3}{g.\alpha}} \quad (21)$$

For $S = 1,5 \text{ m}$, $g = 9,81 \text{ m/s}^2$ one obtains:

$$R_{opt} = \sqrt{\frac{5,5046.V^3}{\alpha}} = 2,35 \cdot \sqrt{\frac{V^3}{\alpha}} \quad (22)$$

If instead of the cant ramp slope $k = 10 * V$ a slope value of $k = 8 * V$ is used:

$$\alpha = \frac{28,8.S.V^3}{g.R^2}$$

$$R_{opt} = \sqrt{\frac{28,8.S.V^3}{g.\alpha}} = \sqrt{\frac{4,4037.V^3}{\alpha}} = 2,1 \cdot \sqrt{\frac{V^3}{\alpha}} \quad (23)$$

In the case of cant ramp slope $k = 10 * V$ and a normal cant value /equation (7)/:

$$L_{tc} = 36.V * \left(\frac{8,3,6^2.V^2_{[m/s]}}{R} \right) = 3,732 \cdot \frac{V^3}{R} \quad (24)$$

$$R_{opt} = \sqrt{\frac{3,732.V^3}{\alpha}} = 1,93 \cdot \sqrt{\frac{V^3}{\alpha}} \quad (25)$$

The general form of the expression for the optimal radius at which the shortest horizontal curve is obtained is:

$$R_{opt} = c \cdot \sqrt{V^3/\alpha}, \quad (26)$$

where c is a coefficient depending on the method of determining the cant and the slope of the cant ramp.

4. Practical applicability of the optimal radius

According to the specific method for determining the length of the transition curve and the cant, the use of the optimal radius can give a length of the circular curve D_u less than the minimum allowable in [1].

Short circular curves pose a risk to the dynamics of vehicle movement, especially with higher design speeds. In this section, a condition is derived to prevent obtaining too short circular curves when using the optimal radius.

As mentioned above, the minimum length of a circular curve [1] is:

$$D_{u,min} = \frac{V_{[km/h]}}{2} = \frac{3,6.V}{2} = 1,8.V \quad (27)$$

According to the notations adopted in equations (15-17) the following inequality can be formulated:

$$D_u - L_{tc} \geq D_{u,min} \quad (28)$$

$$\alpha.R - L_{tc} \geq 1,8.V \quad (29)$$

The delta angle α for normal cant can be derived through equation (25):

$$\alpha = 3,732 \cdot \frac{V^3}{R^2} \quad (30)$$

However L_{tc} for normal cant is:

$$L_{tc} = 10,3,6.V * \frac{8,3,6.V^2}{1000.R} = 3,732 \cdot \frac{V^3}{R} \quad (31)$$

Substituting α and L_{tc} in the inequality (29) leads to a contradiction:

$$3,732 \cdot \frac{V^3}{R^2} \cdot R - 3,732 \cdot \frac{V^3}{R} \geq 1,8.V \quad (32)$$

$$0 \geq 1,8.V \quad (33)$$

Obtaining an optimal radius when using normal cant values is not compatible with the regulatory requirements for the minimum length of the circular curve.

A similar check can be made for the use of the minimum allowable cant according to equation (8). In this case α has a value from equation (20).

$$\alpha = \frac{36.S.V^3}{g.R^2} \quad (34)$$

The length of the transition curve is as derived in equation (18):

$$L_{tc} = \frac{36.S.V^3}{g.R} - \frac{36.V.S.A_{cf,max}}{g} \quad (35)$$

Substituting α and L_{tc} in the inequality (29):

$$\frac{36.S.V^3}{g.R^2} \cdot R - \frac{36.S.V^3}{g.R} + \frac{36.V.S.A_{cf,max}}{g} \geq 1,8.V \quad (36)$$

$$\frac{36.V.S.A_{cf,max}}{g} \geq 1,8.V \quad (37)$$

For $S = 1,5 \text{ m}$, $g = 9,81 \text{ m/s}^2$, $A_{cf,max} = 0,65 \text{ m/s}^2$ one obtains:

$$3,578.V \geq 1,8V \quad (38)$$

Obtaining an optimal radius when using the minimum allowable cant is compatible with the regulatory requirements for the minimum length of the circular curve.

From the inequality (37) the residual centrifugal acceleration can be expressed, at which the curve with the optimal radius will be with a length greater than the minimum allowable:

$$\frac{36 \cdot V \cdot S \cdot A_{cf}}{g} \geq 1,8 \cdot V \quad (39)$$

$$\frac{36 \cdot S \cdot A_{cf}}{g} \geq 1,8 \quad (40)$$

$$A_{cf} \geq \frac{1,8 \cdot g}{36 \cdot S} \quad (41)$$

For $S = 1,5$ m, $g = 9,81$ m/s², one obtains:

$$A_{cf} \geq 0,327 \text{ m/s}^2 \quad (42)$$

The above equation can also be expressed with the cant deficiency:

$$D = A_{cf} \cdot \frac{S}{g} = 0,327 \cdot \frac{1,5}{9,81} = 0,05_{[m]} = 50_{[mm]} \quad (43)$$

Conclusion: The methodology given in this report for determining the optimal radius is applicable to curves of the conventional railway where the cant deficiency is greater than 50 mm and the residual centrifugal acceleration is more than 0,327m/s².

Since in the expression for the radius the delta angle is in the denominator, as the angle increases, the resulting radius will decrease. Of interest is the largest delta angle at which the resulting optimal radius will be equal to the minimum radius for a given speed and cant. For curves with a delta angle above the limit, obtaining the optimal radius would be pointless, as the minimum radius will always give the shortest horizontal curve.

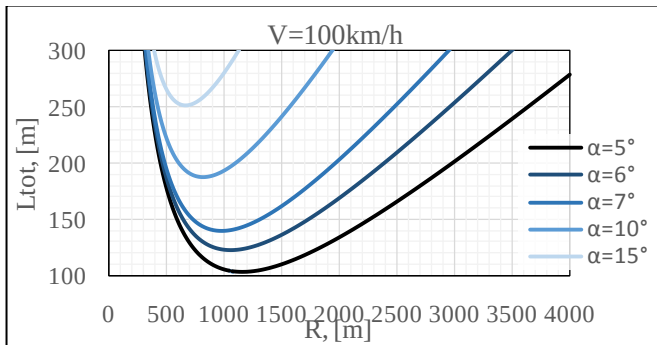


Fig. 5 Total length of railway curve relative to radius and various delta angles

Note: The angle α above is in degrees for the sake of clarity, the given expressions are valid when it is in rad !

Following from equation (4) the minimum radius is:

$$R_{min} = \frac{V^2}{A_{cf,max} + g \cdot \frac{H}{S}} \quad (44)$$

By equating the minimum radius with that derived in (21), the required limit angle is derived as:

$$\alpha_{rp} = \frac{36 \cdot S}{g \cdot V} \cdot \left(A_{cf,max} + g \cdot \frac{H}{S} \right)^2 \quad (45)$$

For $A_{cf} = 0,65$ m/s², $S = 1,5$ m, $g = 9,81$ m/s² and $H = 0,15$ m:

$$\alpha_{rp} = \frac{14,643}{V} \quad (46)$$

Table 1 Limit delta angles for various design speeds

V [km/h]	R _{min} [m]	α_{rp} [°]
80	305	37.7542
90	385	33.5593
100	475	30.2034
120	685	25.1695
160	1215	18.8771

5. Conclusion

The expressions defined in this report can be easily adapted and used under different conditions and regulatory requirements in cases where it is necessary to obtain a maximum length of a straight section of the railway line between two horizontal curves. If the two directions between which a curve must be designed, as well as the design speed are available, an optimal radius is derived, the use of which would lead to a minimum length of the curve.

6. Literature

1. Ordinance № 55 of 29 January 2004 On the design and construction of railway lines, railway stations, level crossings and other elements of railway infrastructure, Ministry of Transport
2. COMMISSION REGULATION (EU) No 1299/2014 of 18 November 2014 on the technical specifications for interoperability relating to the 'infrastructure' subsystem of the rail system in the European Union
3. Order №601/21.03.2018r. of the General Director of the NRIC
4. Iwnicki s., Spiryagin M., Cole C. Mcsweeney T. "Handbook of railway vehicle dynamics, second edition", CRC PRESS, 2019
5. Instruction for construction and maintenance of the superstructure of the railway and railway switches, NRIC, Sofia, 2018
6. Todorov S. „Design and construction of railways“ , Sofia, 2006

Disturbance rejection in a one-half vehicle suspension using a fuzzy controller

Katerina Hyniova

Faculty of Information Technology– Czech Technical University in Prague, Czech Republic
hyniova@fit.cvut.cz

Abstract: Generally, passenger ride comfort can be interpreted as an attenuation of sprung mass acceleration or as peak minimization of sprung mass vertical displacement, while good handling can be characterized as an attenuation of unsprung mass acceleration. This effort devoted to passive suspension design is ineffective because improvements to ride comfort are achieved at the expense of handling and vice versa. Instead, the best result can be achieved by active suspension, i.e. when an additional force can act on the system and simultaneously improve both of these conflicting requirements. Another important goal of the control design is to maintain robustness of the closed loop system. In the paper, fuzzy logic is used to simulate active suspension control of a one-half-car model. Velocity and acceleration of the front and rear wheels and undercarriage velocity above the wheels are taken as input data of the fuzzy logic controller. Active forces improving vehicle driving, ride comfort, and handling properties are considered to be the controlled actuator outputs. The controller design is proposed to minimize chassis and wheels deflection when uneven road surfaces, pavement points, etc. are acting on tires of running cars. As a result, a comparison of an active suspension fuzzy control and a spring/damper passive suspension is shown using MATLAB simulations.

Keywords: ACTIVE SUSPENSION, FUZZY LOGIC, CONTROL, ONE-HALF-CAR MODEL, SIMULATION

1. Introduction

At the Czech Technical University in Prague various alternative strategies and innovations to classical passive suspension systems improving ride comfort of the passengers, providing steering stability, maximizing safety, and improving handling properties of vehicles has been researched. In order to improve handling and comfort performance instead of a conventional static spring and damper passive system, an alternative active suspension system has been developed. Certainly, there are numerous variations and different configurations of vibration suspension. In known experimental active systems the force input is usually provided by hydraulic or pneumatic actuators. As an alternative approach to active suspension system design, electromechanical actuators have been studied by the research group. Such actuators provide a direct interface between electronic control and the suspension system. Connection of a passive spring-damper suspension to an active system has a potential of improving safety and comfort under nominal conditions. Perhaps more important is that such a combination allows continuous adaptation to different road surface quality and driving situations.

A number of studies on structural vibration control have been done recently and practical applications have been realized [1]. It is used both, passive solutions for vibration isolation, and active systems, usually based on PID controllers. In addition, semi-active vibration isolation methods are often proposed and used. Liu *et al.* [3] designed a slightly more intricate fuzzy controller for a magneto-rheological damper and were able to reduce vibrations of single-degree of freedom bridge model subjected to random inputs. Simulation of active vibration isolation of a one-quarter-car model with fuzzy logic device has been designed by Nastac [4].

2. Problem Formulation

For the design of active suspension, we know how to create a suspension model and how to define objectives of control in order to reach a compromise between contradictory requirements like ride comfort and road holding by changing the force between a wheel and chassis masses. In the past, it has been reported on this problem successively, about the base of optimization techniques, adaptive control and even, H-infinity robust methods [6]. In this paper, fuzzy logic is used to control the active suspension of a one-half-car model that uses linear electrical motor as an actuator. There are taken velocity and acceleration of the front and rear wheels and undercarriage velocity and vertical acceleration above these wheels as input data of the fuzzy logic controller, and active forces f_1 and f_2 as its output data. The objective of fuzzy control is to minimize

chassis deflections to reach passenger comfort and wheels (not to damage the road surface, respectively) when road disturbances are acting upon the running car.

Passenger comfort can be interpreted as an attenuation of sprung mass acceleration or as peak minimization of sprung mass vertical displacement, while good handling can be characterized as an attenuation of unsprung mass acceleration. This effort devoted to passive suspension design is ineffective because improvements to ride comfort are achieved at the expense of handling and vice versa. Instead, the best result can be achieved by active suspension, i.e. when an additional force acts on the system and simultaneously improves both of these conflicting requirements. Another important goal of the control design is to maintain robustness of the closed loop system.

3.Active Suspension System

All suspension systems are designed to meet various specific requirements. In suspension systems, mainly two most important points are supposed to be improved – vibrations absorbing (videlicet passenger comfort) and attenuation of the disturbance transfer to the road (videlicet car handling). The first requirement could be understood as an attenuation of the sprung mass acceleration or as a peak minimization of the sprung mass vertical displacement. The second one is characterized as an attenuation of the force acting on the road or – in simple car models – as an attenuation of the unsprung mass acceleration. The goal is to satisfy both these contradictory requirements.

Satisfactory results can be achieved when an active suspension system generating variable mechanical force acting between the sprung and unsprung masses is used.

Such an actuator can be a linear electric motor [2]. In comparison with traditional actuators that use revolving electromotors and a lead screw or toothed belt, the direct drive linear motor enables contactless transfer of electrical power according to the laws of magnetic induction. The gained electromagnetic force is applied directly without the intervention of mechanical transmission. Linear electric motors are easily controllable and for features like low friction, high accuracy, high acceleration and velocity, high values of generated forces, high reliability and long lifetime. Their usage as shock absorbers seems to be ideal.

Fig.1 shows the basic principle and structure of the linear electric motor used as an actuator in the designed unique active suspension system. The appreciable feature of linear motors is that they directly translate electrical energy into usable mechanical force and motion and back. They are linear shaped.

Linear motor translator movements reach high velocities (up to approximately 4 m/s), accelerations (up to g multiples) and forces (up to 10 kN). The electromagnetic force can be applied directly to the payload without an intervention of mechanical transmission.

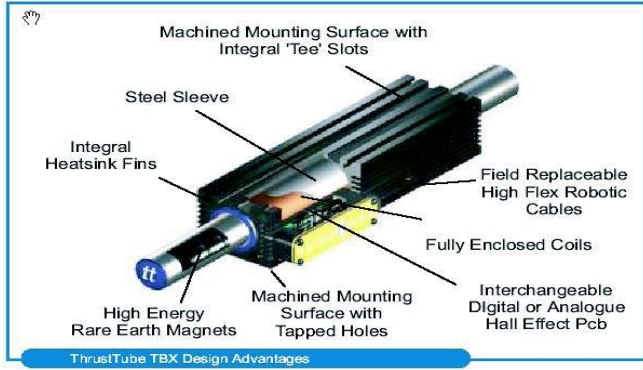


Fig. 1 Linear motor basic design (manufacturer spread sheet).

4.Linear Motor Model

In order to verify control algorithms we created a linear motor model including a power amplifier in Matlab/SimulinkTM. The model enables to demonstrate the conversion of electrical energy to mechanical energy.

In the model, it is assumed that the magnetic field of the secondary part with permanent magnets is sinusoidal, the phases of the primary part coils are star-connected, and a vector control method is used to control the phase current [6]. Here, PWM voltage signal is substituted by its mean value to shorten (about 10 times) the simulation period (inaccuracies caused by such a substitution can be neglected).

The principal inner representation of the model is shown in Fig.2. The model input vector is given by the instantaneous position [m] necessary to compute the commutation current of the coils, instantaneous velocity [m/s] (the induced voltage of the coils depends on the position and velocity) and desired force [N].

The designed model function we verified comparing dynamics of the model in Fig.3 and the real motor. The simulation parameters correspond to catalogue parameters of TBX3810 linear motor fy Thrust-tube.

For example, time responses caused by changes of the desired force have been compared.

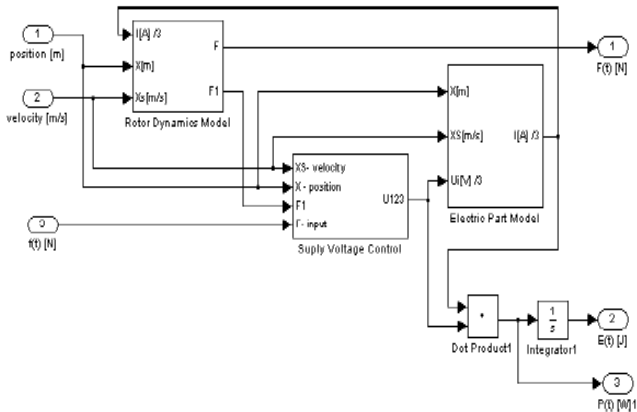


Fig.2. Principal inner model representation.

The linear motor input-output model is shown in Fig. 3.

Fig.4 and Fig.5 represent simulated and real time responses, respectively (rightangular force signal: 0→200 [N], power supply of 150 [V], velocity: 0 [m/s]).

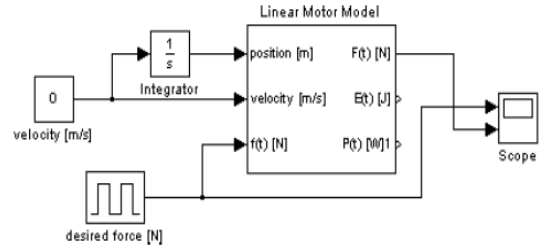


Fig. 3 Linear motor input/output model for dynamics verification.

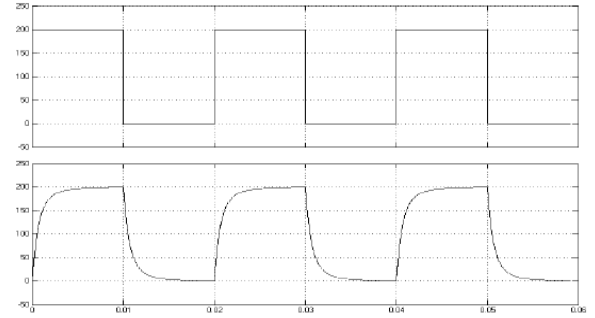


Fig.4 Simulated time response.

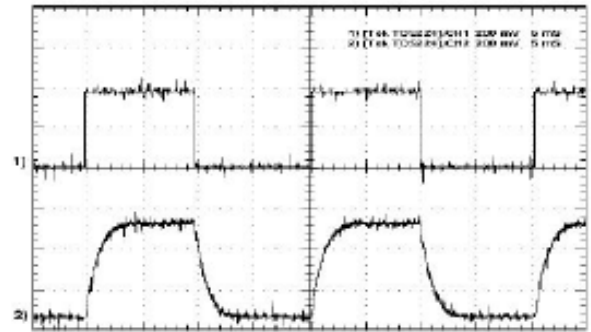


Fig.5 Real time response.

Comparing the time responses in Fig.4 and Fig.5 it can be seen very good matching of the model and the real motor behavior.

On the base of the experiments that were taken on the model, we gained values of electric power necessary to be supplied or consumed when velocity and force of the motor are constant.

In Fig. 6 an input/output model of the linear motor (with concrete simulation values) is represented.

It results from many experiments we made [6] with TBX3810 linear motor that the designed model describes the real linear motor equipped with necessary auxiliary circuits very authentically and enables to verify control algorithms developed to control the linear motor as an actuator of the active suspension system.

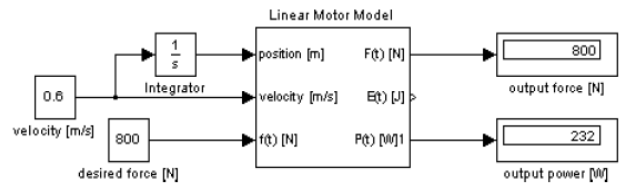


Fig.6 Linear motor input-output model.

5.One-half-car Suspension Model

In this paper, a one-half-car model in Fig.7 which includes two one-quarter-car models connected to a homogenous undercarriage [2] is considered.

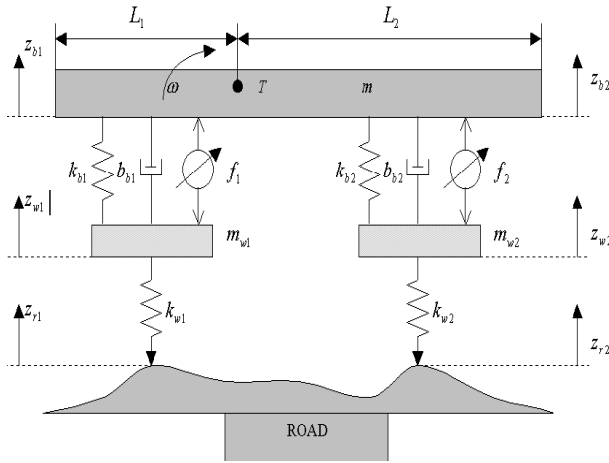


Fig. 7 One-half-car model.

The undercarriage is determined by its mass - m [kg] (taken as one half of the total body mass - 500 kg), length L [m] ($L = L_1 + L_2 = 1,5m + 2,5m = 4m$), center of gravity position T [m] (given by L_1 and L_2) and moment of inertia $J_p = 2700 \text{ kgm}^2$.

The motion equations of the car body and the wheels are as follows:

$$m_{w1} \ddot{z}_{w1} = -f_1 + k_{b1}(z_{b1} - z_{w1}) - k_{w1}(z_{w1} - z_{r1}) + b_{b1}(\dot{z}_{b1} - \dot{z}_{w1}) \quad (1)$$

$$m_{w2} \ddot{z}_{w2} = -f_2 + k_{b2}(z_{b2} - z_{w2}) - k_{w2}(z_{w2} - z_{r2}) + b_{b2}(\dot{z}_{b2} - \dot{z}_{w2}) \quad (2)$$

$$m_{b1} \ddot{z}_{b1} = f_1 - k_{b1}(z_{b1} - z_{w1}) - b_{b1}(\dot{z}_{b1} - \dot{z}_{w1}) = F_1 \quad (3)$$

$$m_{b2} \ddot{z}_{b2} = f_2 - k_{b2}(z_{b2} - z_{w2}) - b_{b2}(\dot{z}_{b2} - \dot{z}_{w2}) = F_2 \quad (4)$$

where the position variables are taken with respect the static equilibrium position, m_{w1} , m_{w2} - wheel masses (35 kg each), k_{b1} , k_{b2} - passive suspension spring stiffnesses (16 kN/m each), k_{w1} , k_{w2} - tire stiffness (160 000 N/m each), b_{b1} , b_{b2} - passive suspension damping coefficients (980 Ns/m each), f_1 , f_2 - active forces between the front/rear sprung and unsprung masses [N], z_{r1} , z_{r2} - road displacements [m], z_{b1} , z_{b2} - body (chassis) displacements [m], z_{w1} , z_{w2} - wheel displacements [m].

To model the road input, we assume that the vehicle is moving at a constant forward speed. Then the vertical velocity is a white noise process which is approximately true for most of real roadways.

The pitching equation is given as :

$$F_1 L_1 - F_2 L_2 + J_p \dot{\omega} = 0 \quad (5)$$

and motion of the gravity center as:

$$F_1 + F_2 - m_p \dot{v}_r = 0 \quad (6)$$

Note, that:

$$v_{b1} = v_r + \omega L_1 \quad (7)$$

and

$$v_{b2} = v_r - \omega L_2 \quad (8)$$

where the meaning of constants and variables is as follows:
 v_r [ms^{-1}] - velocity of the center of gravity, ω [rad s^{-1}] - angular velocity, v_{b1} [ms^{-1}] - undercarriage velocity above the front wheel, and v_{b2} [ms^{-1}] - undercarriage velocity above the rear wheel.

6. State-space Model

To transform the motion equations of the one-half-car model to a state space model, the following state variables vector x (9), input variables vector u (14), and the vector of disturbances v (15), are considered:

$$x = [x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8]^T \quad (9)$$

where:

$$x_1 = z_{b1} - z_{w1} \quad x_5 = z_{w2} - z_{r2} \quad (10)$$

$$x_2 = z_{w1} - z_{r1} \quad x_6 = z_{w2} \quad (11)$$

$$x_3 = \dot{z}_{w1} \quad x_7 = v_r \quad (12)$$

$$x_4 = z_{b2} - z_{w2} \quad x_8 = \omega \quad (13)$$

$$u = [f_1, f_2]^T \quad (14)$$

$$v = [z_{r1}, z_{r2}]^T \quad (15)$$

Then the motion equation of the one-half-car model for the active suspension can be written in the state space form as follows:

$$\dot{x} = Ax + Bu + Fv \quad (16)$$

where for the given data A , B and F are derived in [4][6].

Thanks to the negative real parts of all eigen values of matrix A , the model is stable.

7. Fuzzy Logic Controller

The fuzzy control system consists of three stages: fuzzification, fuzzy inference and defuzzification (Fig.8).

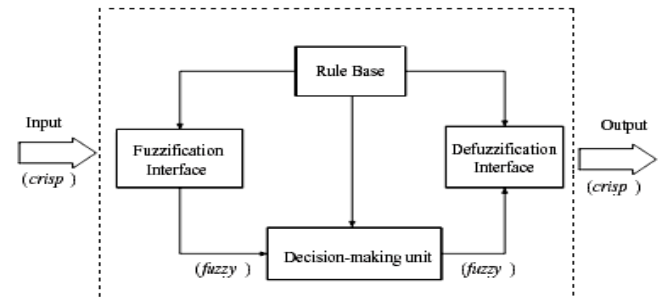


Fig.8 Fuzzy controller structure

The fuzzification stage converts real-number (crisp) input values into fuzzy values whereas the fuzzy inference machine processes the input data and computes the controller outputs in cope with the rule base and data base. These outputs, which are fuzzy values, are converted into real-numbers by the defuzzification stage.

The fuzzy logic controller used for the active suspension has nine inputs:

$$[v_{b1}, \dot{v}_{b1}, v_{b2}, \dot{v}_{b2}, v_{w1}, \dot{v}_{w1}, v_{r}, \dot{v}_r, \omega]^T \quad (17)$$

and two outputs: f_1 and f_2 . All membership functions are of triangular form. Variables ranges are stated experimentally [2] and are given in Tab.1a and Tab.1b below.

Table 1a: Variables ranges

z_r [cm]	$ f_1 _{max}$ [N]	$ f_2 _{max}$ [N]	$ v_r _{max}$ [m.s ⁻¹]	$ \dot{v}_r _{max}$ [m.s ⁻²]	ω [rad.s ⁻¹]
5	2876,4	2949,4	0,3	6,6	0,1
10	5752,8	6062,5	0,5	13,5	0,2

Table 1b: Variables ranges

$ v_{b1} _{max}$ [m.s ⁻¹]	$ \dot{v}_{b1} _{max}$ [m.s ⁻²]	$ v_{w1} _{max}$ [m.s ⁻¹]	$ v_{b2} _{max}$ [m.s ⁻¹]	$ \dot{v}_{b2} _{max}$ [m.s ⁻²]	$ v_{w2} _{max}$ [m.s ⁻¹]
0,3	6,8	2,4	0,3	6,8	2,2
0,5	13,5	4,8	0,5	13,5	4,9

The rule base used in the active suspension system for one-half-car model is represented by 160 rules [4], [6] with fuzzy terms derived by modeling the designer's knowledge and experience.

There are two types of rules for the one-half-car model. The rules for unsprung masses are corresponding to the rules of the one-quarter-car model [4], [6] and considering:

$$[v_{b1}, \dot{v}_{b1}, v_{b2}, \dot{v}_{b2}, v_{w1}, v_{w2}]$$

as fuzzy controller inputs, and f_1 and f_2 as controller outputs.

The abbreviations used in Table 2 and Table 3 correspond to:

- NV Negative Very Big
- NB..... Negative Big
- NM.....Negative Medium
- NS..... Negative Small

- ZR..... Zero
- PS..... Positive Small
- PM.....Positive Medium
- PB..... Positive Big
- PV.....Positive very Big

The output of the fuzzy controller is a fuzzy set of control forces. As processes usually require non-fuzzy values of control, a method of defuzzification called “center of gravity method” is used here [2], [4], [6].

Table 2: Rules for Unsprung mass

$If [v_{w1}=PM]AND[v_{b1}=NM]AND[\dot{v}_{b1}=P]THEN[f_1=PV]$
$If [v_{w1}=PS]AND[v_{b1}=NS]AND[\dot{v}_{b1}=P]THEN[f_1=PB]$
$If [v_{w1}=PM]AND[v_{b1}=NM]AND[\dot{v}_{b1}=ZE]THEN[f_1=PM]$
$If [v_{w1}=PS]AND[v_{b1}=NS]AND[\dot{v}_{b1}=ZE]THEN[f_1=PS]$
$If [v_{w1}=NM]AND[v_{b1}=PM]AND[\dot{v}_{b1}=P]THEN[f_1=NV]$
$If [v_{w2}=PM]AND[v_{b2}=NM]AND[\dot{v}_{b2}=P]THEN[f_2=PV]$
$If [v_{w2}=PS]AND[v_{b2}=NS]AND[\dot{v}_{b2}=P]THEN[f_2=PB]$
$If [v_{w2}=PM]AND[v_{b2}=NM]AND[\dot{v}_{b2}=ZE]THEN[f_2=PM]$
$If [v_{w2}=PS]AND[v_{b2}=NS]AND[\dot{v}_{b2}=ZE]THEN[f_2=PS]$
$If [v_{w2}=NM]AND[v_{b2}=PM]AND[\dot{v}_{b2}=P]THEN[f_2=NV]$

Table 3: Rules for Sprung mass

$If [v_T=PS]AND[\omega=PM]AND[\dot{v}_T=P]THEN[f_1=NV]AND[f_2=PM]$
$If [v_T=NS]AND[\omega=PM]AND[\dot{v}_T=P]THEN[f_1=NM]AND[f_2=PV]$
$If [v_T=NM]AND[\omega=PM]AND[\dot{v}_T=P]THEN[f_1=ZE]AND[f_2=PV]$
$If [v_T=PS]AND[\omega=PS]AND[\dot{v}_T=P]THEN[f_1=NB]AND[f_2=PS]$
$If [v_T=ZE]AND[\omega=PS]AND[\dot{v}_T=P]THEN[f_1=NB]AND[f_2=PB]$
$If [v_T=NS]AND[\omega=PS]AND[\dot{v}_T=P]THEN[f_1=NS]AND[f_2=PB]$
$If [v_T=PS]AND[\omega=NS]AND[\dot{v}_T=P]THEN[f_1=NV]AND[f_2=PV]$
$If [v_T=NS]AND[\omega=NS]AND[\dot{v}_T=P]THEN[f_1=PS]AND[f_2=NB]$
$If [v_T=PS]AND[\omega=NM]AND[\dot{v}_T=P]THEN[f_1=PM]AND[f_2=NV]$
$If [v_T=NS]AND[\omega=NM]AND[\dot{v}_T=P]THEN[f_1=PV]AND[f_2=NM]$

8. Simulation Results

In this section, the controller was tested in order to compare the results of the designed fuzzy logic control with a traditional passive suspension system. As an example, step responses of the unsprung and front/rear sprung masses are shown in Fig.8- Fig.11.

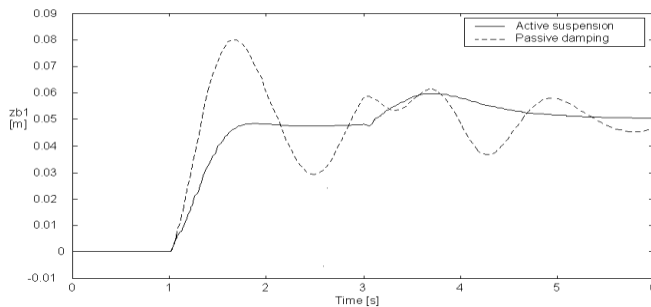


Fig.8 Sprung mass deflection above front wheel.

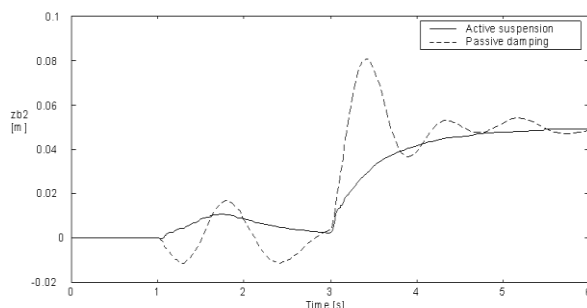


Fig.9 Sprung mass deflection above rear wheel.

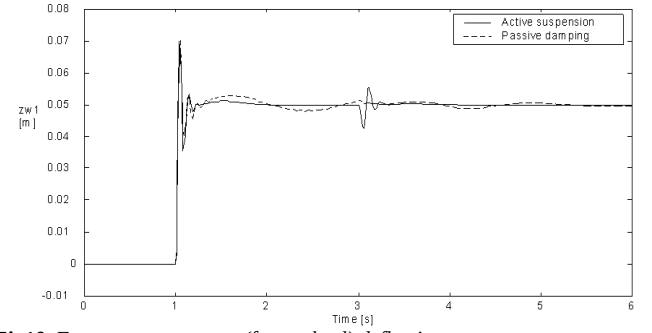


Fig10 Front unsprung mass (front wheel) deflection.

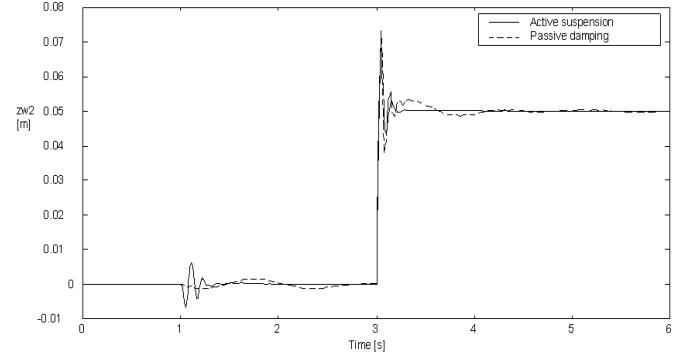


Fig.11 Rear unsprung mass (rear wheel) deflection

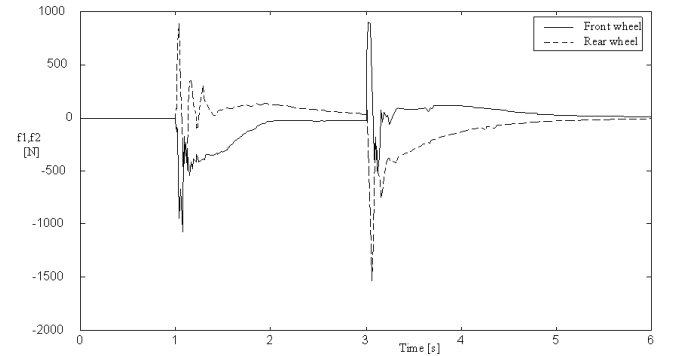


Fig.12 Active forces acting on front/rear wheel.

From Fig.9 and Fig.10, it is evident that fuzzy controlled active suspension efficiently suppresses sprung mass oscillations that occur when only passive suspension is used.

Diagram in Fig. 13 represents active forces acting on front and rear wheels in order to optimize ride comfort and good handling of the vehicle.

9. Conclusion

In the paper, we briefly described a basic way of fuzzy controlled active suspension system designed for a vehicle one- half-car model.

The entire analysis was developed in Matlab - Simulink, with Fuzzy Logic Toolbox. The fuzzy inference machine is also on custody of a special module of Simulink. Practically, the entire process of fuzzification - inference - defuzzification is automaton made by the Fuzzy Logic Controller of Simulink. The inference machine operation is based on the set of rules which link the input variables by the outputs. The set of input variables, output variables and inference rules base derived by modeling the designer's knowledge and experience on vibroisolation devices.

The simulation results have been successfully verified on an experimental test stand. The same configuration like in Fig.7 has been used for test stand design and real experiments. Mechanical configuration of the test stand is obvious from Fig.13. Under the tire there is placed another linear electric motor that uses an input

experimental signal described in [6] to generate road displacement (road deviations) under the running wheel.



Fig.13 Experimental test stand

As is mentioned in [2],[4] the controller is developed via Matlab implemented into dSpace a connected to the test stand system.

Acknowledgement: This research has been supported by the MSMT CR project INTER VECTOR No. LTV 17019.

References

- [1] Cuclu, R.: Fuzzy Logic Control of Vibration of Analytical Multi-Degree-of- Freedom Structural Systems, Turkish J. Eng. Env. Sci., p157-167, 2003
- [2] Hyniova, K. - Stribrsky, A. - Honcu, J.: Fuzzy Control of Mechanical Vibrating Systems, Proceedings of the International Carpatian Control Conference ICCS 2001, pp. 393-398, Krytica, Poland, 2001
- [3] Liu, Y.: Energy minimization-based vibration control of a bridge using magneto-rheological fluid dampers, Proceedings of SPIE, 2000
- [4] Nastac, S.: Simulation of active Vibration Isolation with Fuzzy Logic Device, In: Proceedings of the 10th international Conference on mathematical and computational methods in Science and Engineering (MACMESE '08), pp. 346-351) Brasov, 2008.
- [5] Stribrsky, A. - Hyniova, K. - Honcu, J.: Using Fuzzy Logic to Control Active Suspension of Vehicles, Intelligent Systems in Practice, pp.41-49, Luhacovice, 2000
- [6] Stribrsky, A. - Hyniova, K. - Honcu, J.: Reduction of Vibrations in Mechanical Systems, Proceedings of Workshop 2001, Part A, pp.174-175, CTU Prague, 2001

Application of photogrammetry in the analysis of vehicle collision processes

Željko Šarić¹, Krešimir Ećimović², Andrej Kunštek¹, Tomislav Kučinić¹
 Faculty of Traffic and Transport Sciences¹ – University of Zagreb, Croatia
 Technical School Daruvar² - High school Daruvar, Croatia
 zeljko.saric@fpz.unizg.hr
 kresimir.ecimovic@gmail.com
 andrej.kunstek@fpz.unizg.hr
 tomlav.kucinic@fpz.unizg.hr

Abstract: The analysis of each traffic accident is carried out based on recorded traces at the scene of the traffic accident and the damage caused to vehicles. One of the basic parameters in the analysis of traffic accidents is the mutual position of the vehicle at the time of the collision. To define the collision position of the vehicle, it is necessary to determine the intensity and compliance of the vehicle damage. The development of photogrammetry has enabled the creation of 3D models based on which the intensity and mutual compliance of vehicle damage can be more clearly shown, which increases the relevance of the determined collision position of the vehicle. Accordingly, this paper will present the process of creating 3D models of damaged vehicles and will analyze all the possibilities of applying photogrammetry in defining the collision positions of vehicles.

Keywords: TRAFFIC ACCIDENTS, PHOTOGRAMMETRY, VEHICLE 3D MODELS, VEHICLE COLLISION.

1. Introduction

After the collision process of one or more vehicles, it is necessary to enable the forensic expert to reconstruct the collision process based on the investigation and calculate the necessary parameters. One of the most important parameters is the speed of the vehicle before the collision. Today's vehicles are much more resilient and can absorb much more energy in a collision process than vehicles twenty or more years ago. In the design of passenger cars, there are different types of bodies: sedan, convertible sedan, coupe, extended sedan, van, convertible, multi-purpose vehicles and special vehicles. Apart from the type, it is more important to differentiate the body according to the construction of the superstructure. There are three basic types of body construction: separate body, body with load-bearing frames and self-supporting body.

The most used materials for vehicle body construction are steel, galvanized steel, aluminium sheets, plastics and composite materials. Carbon fiber is increasingly used in sports cars due to its very good properties and strength-to-weight ratio. The bodywork as such is an important part of passive vehicle safety. The role of passive body safety is to mitigate as much as possible the impact of vehicle kinetic energy in a traffic accident. To mitigate the impact of impact kinetic energy, the bodywork must be solid, torsional, tensile, and compressive, bending, and thermal stress resistant.

The body can be divided into internal and external safety area. Internal safety reduces the risk of injury to the vehicle's passenger compartment by reducing acceleration and forces acting on passengers and the driver. The aim of the measures is to ensure the survival of passengers and drivers and to ensure the operation of those systems that affect the safe removal of passengers. According to the analysis of traffic accidents, the most common causes of injuries to passengers are direct (direct, frontal) collisions with 60 - 65% and side collisions with 20 - 25%.

The materials used in the design of the structure are adapted to absorb as much kinetic energy as possible during the collision. Today's vehicles would have to pass a crash test to be on the market, and important data on the speed and amount of damage are collected from these tests.

The application of photogrammetry in the creation of 3D models of the vehicle involved in the collision makes it easier to determine the damage and determine the speed of the collision.

2. Theoretical basis of photogrammetry

Photogrammetry has been defined by the American Society for Photogrammetry and Remote Sensing as the art, science, and technology of obtaining reliable information about physical objects and the environment through the processes of recording, measuring,

and interpreting photographic images and samples of recorded radiant electromagnetic energy and other phenomena. As the name implies, science originally consisted of photo analysis, however, the use of film cameras has greatly diminished in favor of digital sensors. Photogrammetry has expanded to the analysis of other records, such as digital images, aerial acoustic energy patterns, laser measurements, and magnetic phenomena. [1]

The basic idea of the photogrammetric method is the reconstruction of optical directions, i.e., defining the equations of directions connecting points on an object and their projections in photography. When measuring in space, it is necessary to capture the object from at least two camera positions. The two images then form a stereo pair, and the photogrammetric reconstruction of space using stereo pairs is called stereophotogrammetry. In the past, optical directions have been reconstructed by the optomechanical process using large and expensive devices or stereo instruments. The analysis of the images was lengthy and complicated and limited to specialized measuring institutes, so photogrammetry was rarely used in industry. With the development of digital cameras and computer image processing, automated photogrammetric systems have been developed. The development of the method connected two areas, which are:

- photography and
- metrology.

Due to the need for high accuracy of measurement results, reliability and automation of the photogrammetric system, photographs must be of high quality. Digital cameras are getting better and better day by day, the limits of photo quality and resolution size are constantly shifting, which is important for measurement accuracy. At the same time, the prices of equipment on the market are falling, so the equipment is becoming more widely available. Metrology deals with techniques for determining the 3D coordinates of a measuring object from photographs. [2]

The advantage of this scanning method is that it is not necessary to have physical contact with the object being scanned. With the development of technology, today's sensors for collecting information are, in addition to digital photography, thermal or multispectral cameras. LIDAR systems are also used to create a digital 3D model of the observed object or area.

Areas where photogrammetry is applied:

- forensics,
- archeology,
- architecture,
- building,
- automotive industry,
- medicine,
- mapping of geological information,
- reverse engineering, etc.

For the operation of a computer program in photogrammetry, the basic algorithm is SFM based on stereoscopic photogrammetry. Using the collected photographs taken from various angles around the SFM object, the algorithm allows the determination of the internal and external orientation parameters of the camera. In this way, it is not necessary to enter additional coordinates by geodetic methods, which reduces the complexity of the scanning process itself, but by entering them, the accuracy and speed of the procedure itself is increased. In order for the process to be successful, it is necessary to have as many photos of the object being scanned as possible.

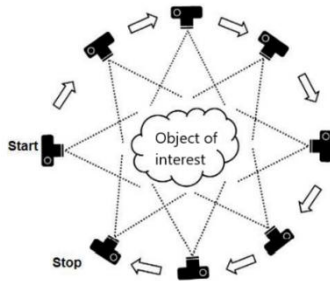


Fig. 1 The way to properly photograph an object for the needs of the SFM algorithm [3]

For each photo, points of interest are detected, and those points are tracked through other captured photos to determine the camera position and coordinates of the captured object. In this procedure, errors occur that can be corrected by using the least squares method for nonlinear functions.

The first and basic problem affecting the SFM algorithm is the determination of three-dimensional coordinates of corresponding features on multiple photographs taken from different angles. The initial step is to identify features in individual photos that can be used to link shots. Today, the established method of solving the latter problem is the SIFT mathematical algorithm. It is a system used to identify features in each shot that are invariant to scale change and rotation, and partially invariant to changes in lighting and camera point of view (Figure 2). Points of interest, that is, the observed features are automatically detected through all scales and all locations in each image. A corresponding descriptive vector is added to each identified and isolated feature. The descriptive vector is obtained by transforming local image gradients into sizes that are quite insensitive to variations in illumination and orientation. The mentioned vectors that describe a particular feature are unique enough to allow the recognition of corresponding features in extremely large data sets. [2]

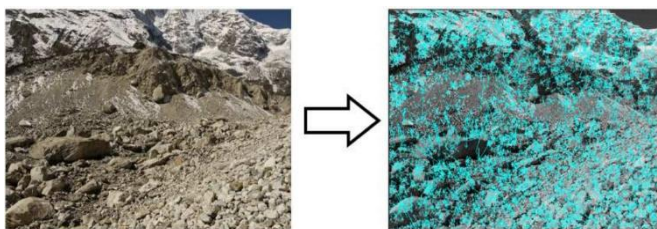


Fig. 2 The SIFT algorithm parses a photo into a database of extracted features

3. Determining the speed of movement of vehicles based on deformations

The expression for the kinetic energy comparison is defined by $\frac{1}{2} \cdot M \cdot ETS^2$, where ETS is the speed at which the comparison is performed in the collision experiment. Regardless of the partial deflection when the vehicle hits a rigid wall, the ETS is identical to the change in speed Δv during the impact process. Assessing damage in real central collisions is not difficult, as there are many attempts to record all types of collisions in the automotive industry.

In the papers stating the conformity of ETS and Δv in the case of real central impacts of two passenger cars, in which the deformations are approximate, there are deviations between the lost speed Δv in the impact process and the size of ETS. Therefore, the impact estimation based on deformations in central impacts has a larger area of scatter in the value of the results. [4]

According to Zeider, F. Deformationsverhalten von Kraftfahrzeugen bei Autoprallversuchen unter praxisgerechten Versuchsbedingungen from 1979, the ETS designation was associated with equivalent speed in testing, but this proved to be a disadvantage because the energy of equivalent speed may deviate from the speed in the test. To avoid this shortcoming, a new expression was introduced - EES. Expressing the speed is done according to the expression:

$$W_d = E_d = \frac{1}{2} m EES^2 \quad (1)$$

where W_d work is spent on deformation [J], E_d - deformation energy [J], m - vehicle mass [kg], EES - energy of equivalent speed [km/h].

In oblique collisions of two vehicles, a part of the kinetic energy of the vehicle is converted into rotational energy. The second part of the kinetic energy is expended on the path of calming during translational motion. Experiments have shown that part of the kinetic energy of vehicle deceleration is less than the part of energy expended on vehicle deformation. [4]

During a collision of a vehicle, permanent deformations of the vehicle occur, for which it is necessary to consume a certain amount of vehicle energy. Energy consumption is the kinetic energy of the vehicle that can be displayed using a virtual amount of speed from the EES. For an authentic assessment of the EES, it is necessary to perform several different crash tests of vehicles in different conditions, because the depressions formed on vehicles by the action of deformation energy depend on different parameters. The amount of deformation energy changes during the collision so that it increases to the maximum value in the compression phase, and in this phase the greatest damage to vehicles occurs, while in the restitution phase the deformation energy decreases and, in this phase, there is a return of partially elastically deformed vehicle material. respectively the return of part of the consumed energy, which causes permanent damage to the vehicle. [5]

The EES value depends only on the bulk energy E_d and the mass of the vehicle m . If the EES value of one of the vehicles involved in the collision of two vehicles is known, then it is possible to determine the EES value of another vehicle if it is unknown. reaction. This can be represented by the following equation: [7]

$$\frac{EES_1}{EES_2} = \sqrt{\frac{m_2 S_{Def1}}{m_1 S_{Def2}}} \quad (2)$$

where m_1 is vehicle 1 mass in [kg], m_2 - vehicle 2 mass [kg], S_{def1} - the depth of the recess of the vehicle 1 caused by the deformation force during the collision of the vehicle in [m], S_{def2} - the depth of the recess of the vehicle 1 caused by the deformation force during the collision of the vehicle in [m], E_d - the energy spent on damage of two vehicles that collided in [J].

If data to determine the deformation energy of colliding vehicles are not available, then the deformation energy of the collided vehicles may be calculated either using a velocity deformation curve based on multiple tests of different vehicle collision speeds or a force displacement curve based on a single impact test. In addition to the above methods, there are other methods for calculating the EES value, namely: the energy grid method (energy grid), approximate equations and algorithms based on damaged vehicles. [5]

When calculating the EES value, the data contained in the EES value catalog, which were obtained from various crash tests of different vehicle models, are most often used. The EES value catalog contains photographs of vehicle damage, which are arranged according to vehicle models and types of collisions. This allows catalog users to calculate the impact strength quickly and reasonably, i.e., the collision speed of the vehicle, based on the EES value, which is based on a visual comparison of the actual damage to the vehicle with those in the EES value catalog. [5]

Delta-V (Δv) is a common notation used in mathematics, and especially in physics to denote a change or difference in velocity. In the context of a motor vehicle collision, Δ specifically refers to the change in speed between the trajectory of the vehicle before and after the collision. [6]

$$\Delta v = v_2 - v_1 \quad (3)$$

where v_1 vehicle speed before collision [m/s], and v_2 - vehicle speed after collision [m/s].

The utility Δ for characterizing collision severity emerged in the 1970s, in the context of collision reconstruction analysis. The National Highway Traffic Safety Administration (NHTSA) has commissioned the development of a collision reconstruction program called CRASH. This program is used to estimate ΔV vehicles involved in a collision based on measurements of their structural deformation. The original version of the CRASH tests was able to estimate the impact speed of the vehicle to an accuracy of about 12% of the actual collision speed. [6]

The EES value reconstruction method is usable only if the value of the EES can be determined from the remaining deformations. A prerequisite for this is good documentation of vehicle damage, which can be seen in the pictures of photo documentation of mostly every traffic accident. Comparative images for determining the EES value are available today from crash tests, and from the automotive industry for comparison. There are several ways of testing that are usually performed at different speeds and for different types of collisions and impacts. There are the following types:

- frontal impact, i.e., a collision of a vehicle with a solid obstacle
- frontal impact into one of the 30 ° oblique obstacles
- frontal impact in a stepped obstacle with 50% coverage
- frontal impact in a stepped obstacle with 30% coverage
- side impact at right angles with a solid impact vehicle
- side impact below 45 ° from the front with a solid impactor
- side impact below 45 ° rear with solid impact vehicle
- impact at the height of the rear window glass with a solid impact vehicle.

For these tests, test speeds (ETS) are known, which means the speeds at which the tests are performed. These ETS data do not always and in all cases correspond to the EES, which should be considered in the assessment. Also, the weight of the tested vehicle and the weight of the test load (hard hit vehicle) should be considered. The results of test values are regularly published in professional journals. [5]

If it is assumed that the vehicles partially penetrate each other, then there is no difference, [5]. If, for example, in the event of a full collision of two vehicles, a thin steel plate is placed between them, the plate would remain in the same place during the collision and can be removed after the collision. The plate has virtually no impact on the collision. If the board is big enough so that drivers can't see it, they would have the impression that they have crossed a solid obstacle. To protect passengers, the crash test determines the maximum values of vehicle deceleration that must not be exceeded (Figure 3). The kinetic energy possessed by the vehicle when hitting an obstacle is converted into deformation work. [7]

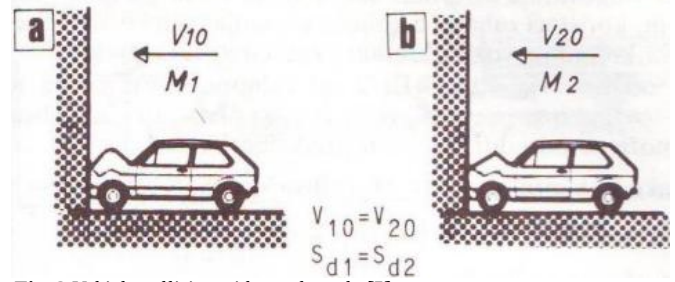


Fig. 3 Vehicle collision with an obstacle [5]

If vehicles have the same dimensions, strike an obstacle at the same speeds, and have the same deformation path (Figure 3), then the following equation holds, [5]:

$$E_{k1} = \frac{M_1 \cdot v_{10}^2}{2}; E_{k1} = \frac{M_2 \cdot v_{20}^2}{2} \quad (4)$$

To facilitate the assessment of vehicle damage and the calculation of energy consumption during vehicle collisions, a catalog has been prepared that includes a wide range of vehicles and their damage. This catalog is updated daily with new examples and results of accidents for each vehicle, thus reducing error and increasing accuracy in the calculation. For the time being, when using EES, optical comparison is preferred over computer comparison, due to a better assessment of the damage in the photographs of the damaged vehicle. Collision tests are used as a basis for computational analysis, from which impact forces are measured, and quantities such as impact speed, vehicle mass, etc. are known. In addition to the reconstruction of traffic accidents, the EES is also used in insurance companies in the analysis of collisions.

3.1. Energy grid for collision analysis purposes

According to Campbell's work, the starting point is that during a frontal impact, i.e., a collision with a solid obstacle, a certain deformation of the vehicle occurs, which is a function of the impact speed (EBS - Equivalent Barrier Speed). [5] The procedure of reliable determination of deformed energy is based on a new model which involves the construction of specific energy raster diagrams for each make, type and model of vehicle. At the very beginning of this procedure, it is necessary to perform the percentage and geometric redistribution of deformed energy over the entire width of the vehicle.

Vehicle impact tests on a fixed obstacle can establish a relationship between deformation and known speed in the test. Based on the known impact speed of a solid fixed obstacle, the degree of strength of the vehicle can be determined, and on the basis of the measured values of deformations. The strain width w_0 is divided into six equal areas in which the strain depth is measured from C_1 to C_6 (Figure 4). For the known width of the vehicle, the weight of the vehicle, the amount of speed up to which there are no visible deformations b_0 and the test speed of impact on the obstacle V_b , the vehicle strength is obtained as follows: [8]

$$S = B \cdot (\text{vehicle width}) \quad (5)$$

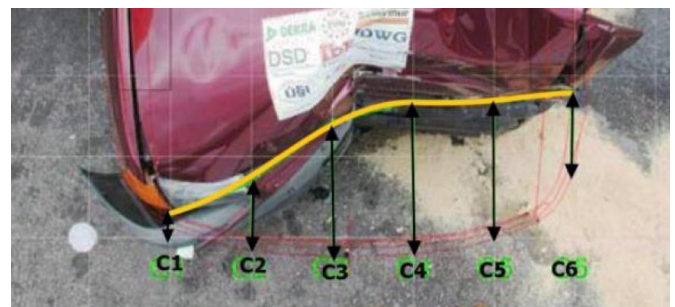


Fig. 4 Measurement of deformation depth [8]

During the investigation of the traffic accident, the technician photographs the deformations of the vehicles involved in the traffic accident. The way the photo documentation of deformed vehicles is carried out is very important and should be carried out according to the rules of the profession. It is important that when photographing certain parts of the vehicle that have suffered deformations, a meter is also photographed so that the depressions can be read later from the photographs. With the help of software tools, recesses can later be displayed in scales from which the work consumed for this deformation can be calculated, and the impact speed can be calculated using expression (6).

$$EBS = \sqrt{\frac{2 \cdot W_{def}}{m}} \quad (6)$$

where W_{def} is the total value of the deformed work on the vehicle [J], and m - total vehicle mass [kg].

4. Research methodology and equipment

For photographing a damaged vehicle from all angles, the use of an unmanned aerial vehicle, the so-called drone, because it is not possible to cover all corners of the vehicle with a classic camera. When shooting with a handheld camera, it is not possible to take photos above your height, and there is a need to use a drone. For the end result to be as accurate as possible, it is necessary to shoot the damaged vehicle from all angles and with sufficient folding of photos for easier processing in software tools for photogrammetry.

4.1. Drone DJI Phantom 4 PRO photography

For photography, the Phantom 4 PRO drone (Figure 5) was used, which provides the possibility of stable flight and shooting in high resolutions. The drone has four engines located on the edges of the aircraft, which allows it a stable flight and easy handling. A remote control is required to operate the drone. For safer control and flight of the drone, it has built-in sensors that prevent the drone from colliding with obstacles around it. The Phantom 4 PRO drone has a built-in 1-inch camera and a 20-megapixel CMOS sensor. The drone camera has a mechanical shutter that eliminates distortions that occur when shooting objects when the camera is moving, and this feature is very important in photogrammetry and therefore this drone with a built-in camera has an advantage over others that do not have this feature.



Fig. 5 DJI Phantom 4 PRO drone [9]

4.2. Agisoft Metashape software tool

Agisoft Metashape is a software tool for photogrammetry and one of the most popular in the sector. Using high-resolution photographs, the program can use the photogrammetry technique to generate 3D models of photographed objects. The application of this software tool is in various industries, e.g., in the computer game industry, in construction, in traffic, geodesy, etc.

By loading and uploading photos, the photos need to be aligned. The program calculates the position of each photo around the photographed object, and it is possible to determine the accuracy: small (25% of possible), medium (50% of possible) and high

(100%). The program requires a lot of working memory on the computer. The more photos, the more working memory is needed.

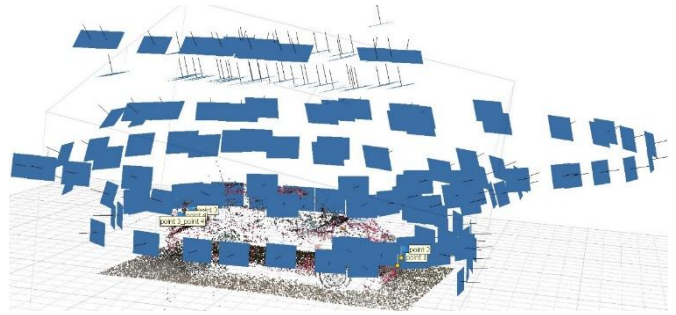


Fig. 6 Display of the sorting of photos in Agisoft Metashape

The next step in the Agisoft Metashape software tool is to generate a dense cloud model. After calculating the camera position, the program calculates the depth information of each camera. Depth information is merged into one point called a dense point cloud. In order to make the calculation as good as possible, it is necessary to select the maximum amount in the program that is possible depending on the hardware capabilities of the machine. As with the previous step, this part depends on the amount of working memory, and 32 GB and more is recommended.



Fig. 7 Building dense points in Agisoft Metashape

With the data from the previous step, it is possible to create a network, i.e., a polygon - mesh. The program offers several methods for building polygons, and Arbitrary is the option that best suits this model. Before starting this step, it is necessary to determine the maximum number of polygons and points. In the model shown in the figure below, there are 2,239,419 polygons and 1,120,791 points.

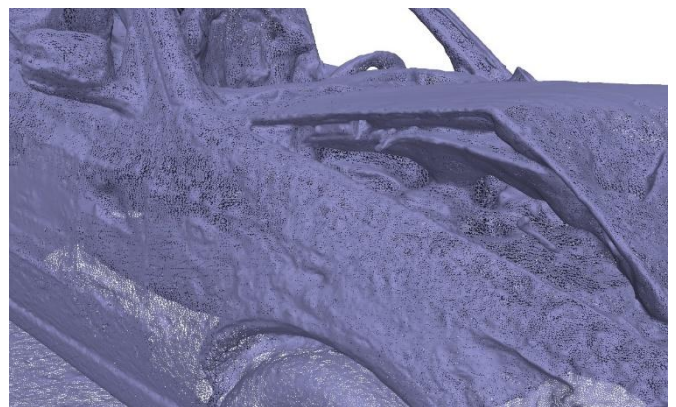


Fig. 8 Display of mesh in Agisoft Metashape

In case the model needs to be exported to another program, such as PC-Crash, it is necessary to optimize the model for easier handling in other programs. One of the basic steps of optimization is to reduce the number of polygons and points. Agisoft Metashape offers this feature called Decimate Mesh. The model above in the picture has too many polygons and too many points. The image below is a comparison of the network before and after optimization.

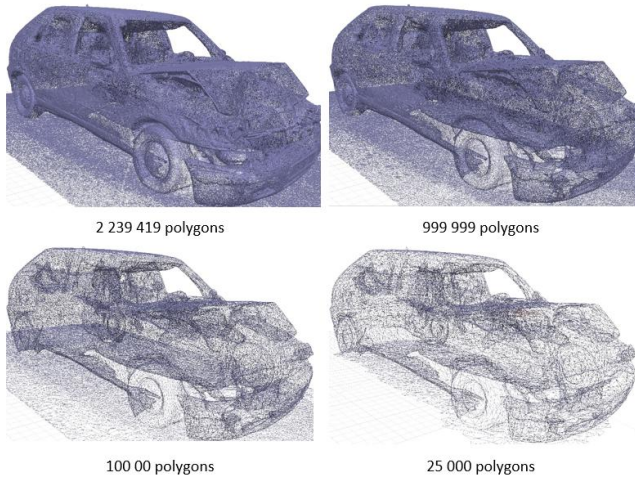


Fig.9 Display of different numbers of polygons after optimization in Agisoft Metashape

Building the texture is the last step in the reconstruction of the vehicle, which is not necessary, but in some cases the reconstruction comes in handy because it allows a more realistic view of the vehicle. Agisoft Metashape offers a total of six different ways to create texture. Figure 10 shows the final texture result on a model of 25,000 polygons.



Fig.10 Display of textured model in Agisoft Metashape

4.3. LIDAR camera Intel Real Sence L515

As part of the experiment, this paper used a LIDAR camera (Light Detection and Ranging), which is a depth camera that uses MEMS mirror scanning technology, providing better laser power efficiency compared to other technologies, with less power consumption of 3.5 W for depth streaming.



Fig.11 LIDAR camera (RealSence L515) [10]

The scanning process begins by registering and installing the DOT3D software tool on your smartphone or laptop. By connecting the LiDAR camera L515 with a USB cable and running the DOT3D software tool, you can start scanning a damaged vehicle. The easiest way is to stick the LiDAR camera on the back of your smartphone

or laptop so that the camera and smartphone are directed to the scan location, as shown in the image below.



Fig.11 Display of LiDAR sensor and smartphone before scanning [11]

When everything is set, scanning is done by looking through the LiDAR camera that is displayed on the smartphone screen. The appearance of green in the place to be scanned indicates that there is enough data so that it can be moved to the next place. Walking around the vehicle with the camera facing it creates a cloud of dots and thus the vehicle is scanned. If the orientation is lost in the process, it is necessary to take a step back for the program to recognize the already scanned parts and continue scanning. The scan result of the two vehicles is shown in the figure below.



Fig.12 Scanned vehicles Škoda Felicia and Renault Thalia

5. Research results and discussion

For this paper, the Department of Traffic Accident Expertise of the Faculty of Transport and Traffic Sciences in Zagreb organized a crash test between two vehicles. The Autodesk AutoCAD software tool was used to display the damage. For the purposes of the comparison, it is necessary to have a 3D model of an undamaged vehicle to be able to compare it with a model of a damaged one. The damage display is shown in Figures 12 and Figure 13, and the 3D model of the undamaged vehicle is shown in green. The 3D model after damage is shown in red.

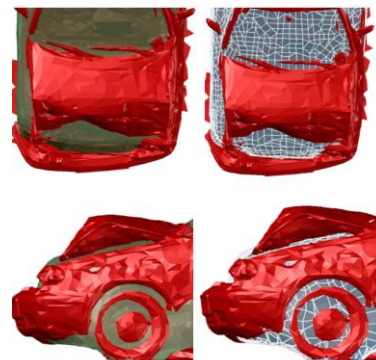


Fig.13 Vehicle damage - side view

The collision position of the vehicle was defined using two methods from this paper - photogrammetry, drone shooting and LiDAR camera recording. The vehicles were prepared and scaled in the Agisoft Metashape program to match the actual dimensions. A known measure on the vehicle is taken for scaling, e.g., the length of the license plates. Several more well-known measures have been taken for more accurate scaling. In practice, special markings are used that are placed on the object before taking photos. Figure 14 shows the collision position of the vehicle with satisfactory overlap and the measured collision angle of 123° .

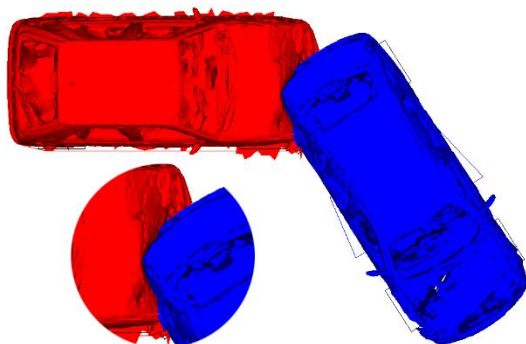


Fig.14 Display of the collision position - floor plan (photogrammetry)

When entering vehicles that were scanned with a LiDAR camera and processed in the DOT3D software tool, the format of the output files from that program was considered. Point Cloud scanned models were entered and cut to obtain the outer contour of the vehicle. With the prepared scanned models, the models are manually adjusted to match the damage as well as possible. The measured angle after adjustment was 114° .



Fig.14 Display of the collision position - floor plan (scanned vehicles)

5.1. Comparison of photogrammetry with the classic photography method in vehicle deformation assessment

For the purposes of this comparison, the EES catalog of vehicles with similar damages as on the tested Škoda Felicia and Renault Thalia vehicles was searched. The Škoda Octavia found in the EES catalog was involved in a car accident with a Renault Kadjar. A Škoda vehicle collided with the front end of the vehicle in front.



Fig.15 Photos of the damaged Škoda Octavia vehicle (EES catalog) and the Škoda Felicia test vehicle

From the photographs collected in the EES catalog, it is difficult to estimate the depth of damage because the photographs were taken from an unfavorable angle for the application of this method. In such a case of determining the depth of damage to the vehicle, only the experience of a forensic expert or the use of some other method to determine the speed of the collision comes to the fore.

For the purposes of this paper, the Department of Traffic Accident Expertise of the Faculty of Transport and Traffic Sciences in Zagreb, organized and performed a "crash" test between two vehicles. A Škoda vehicle (Felicia) collided with a parked Renault (Thalia) vehicle in an organized test. After the test, an investigation was done, and the vehicles were photographed. For the analysis of the traffic accident, in this case of the crash test, the software tool PC-Crash 13.1 was used. This software tool allows the user to reconstruct a traffic accident very accurately and realistically. One of the possibilities of this program is to determine the depth of the damage with the help of a photograph taken on the floor plan (Figure 16).



Fig.16 Display of the depth of damage to the vehicle in the PC-Crash software

In the PC-Crash software, it is necessary to load a photo that was taken from above so that the damage which was caused after the collision can be seen. After scaling the photograph, the deformation line was drawn (green line in Figure 16). Based on this line, the software calculates the difference between the shape of the vehicle before and after the damage and shows the measurement of the depth of damage in eleven points. With these measurements, the program calculates the values of the damaged vehicle (Figure 17). For the program to successfully perform the calculation, a vehicle with similar characteristics is selected from the NHTSA catalog.

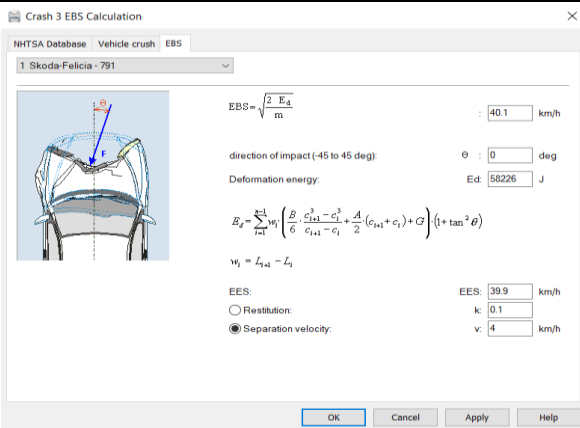


Fig.17 Calculation of EBS value after damage reading

According to the photographs obtained after the investigation, it is sometimes difficult to determine the exact damage and the way the collision occurred. As this is a laboratory experiment, the value of the impact speed of the tested Škoda Felicia vehicle is known, in contrast to the vehicle Škoda Octavia from EES catalog, from the beginning of this chapter. New technologies, such as photogrammetry and LiDAR camera recording, have become very accessible and more cost-effective. The application of the mentioned technologies expands the possibilities of the software tool itself, such as PC-Crash, and serves as an additional input parameter for more accurate calculation or estimation. If a forensic expert had a 3D model of a damaged vehicle after a car collision, he could more easily determine the method by which he would calculate the impact speed. This way of looking allows the expert to look at the vehicle from all angles and distances without any loss in image or model quality. By comparing the difference in damage from Chapter 5, it can be also seen how much the geometry of the vehicle itself is disturbed after the collision.

The picture below shows that the front bumper of the Škoda Felicia remained undamaged in the "crash" test, and this damage would not be suitable for the example of the application of the mentioned method in the third chapter. By displaying a 3D model, the estimator can come to this conclusion faster and easier.



Fig.17 Demonstration of photogrammetry options for determining damage

Vehicles from the EES catalog that have similar damage are taken for comparison, eg the Škoda Octavia from the beginning of this chapter. The damage assessment itself also depends on the estimator's experience, but such a 3D view of the damaged vehicle would allow the less experienced estimator to determine the damage and observe some other parameters after the traffic accident more accurately.

6. Conclusion

Today's vehicles have changed significantly in the way of construction, design, and technology from vehicles more than twenty years ago. This change affected the behavior of the vehicle in the collision process. Vehicles have become more resilient and can absorb more kinetic energy than before. The properties of today's vehicles are a product of the mentioned ways of designing the structure and using several types of materials to absorb as much

kinetic energy as possible during a collision and thus increase the passive safety of drivers and passengers.

A collision of one or more vehicles can have a lot of variations and ways in which it can happen. There are different methods of determining the speed of a vehicle before a collision. Each method has its advantages, disadvantages, and the type of collision to which it can be applied. During each investigation, the vehicles involved in the accident are photographed. By reducing the price of the once expensive technology of digital images and photo processing, the technology of making 3D models from recorded digital photos, photogrammetry, naturally arose.

Photogrammetry is a technology that can generate a 3D model of a captured object from captured photographs using known algorithms and computer processing. The application of this technology in the creation of 3D models of vehicles involved in a traffic accident significantly facilitates the assessment of damage and the level of dents caused by the collision. The symbiosis of this technology with well-known programs, such as PC-Crash, leads to very relevant results in determining the impact speeds and determining the position of the vehicle before the accident.

When the classic method of estimating vehicle deformation after traffic is compared with the new approach via photogrammetry or LiDAR camera, positive shifts in the estimation of deformation depth are obtained. In addition to depth, the estimator has an insight into the 3D model from which you can see many more details of the vehicle, from all angles, which is a significant improvement over classic photogrammetry.

This paper shows the possibilities of applying photogrammetry on the example of a collision process between two vehicles in a crash test at the Faculty of Transport and Traffic Sciences in Zagreb. The vehicles were analyzed and photographed after the collision, so that photogrammetry technologies could be applied to create 3D models. The analysis showed that in this case the damage on the vehicle is not reliable to be relevant to the EES catalog. Without photogrammetry technology, such an assessment would be difficult because it would be made from exclusively classic photographs taken during the inspection.

7. References

1. R.P. Wolf, B.A., Dewitt, B.E., Wilkinson, *Elements of Photogrammetry with Applications in GIS*, (2014)
2. B. Ljubenkov, *Modified photogrammetric method in shipbuilding*, Doctoral thesis, (2006)
3. ResearchGate, <https://bit.ly/2Kk05Qg>, [Accessed: April 2022.]
4. F. Rotim, *Elements of road traffic safety, Volume 3*, Faculty of Transport and Traffic Sciences, Zagreb, (1991)
5. E. Tomasch, *Accident Reconstruction Guidelines*, Graz University of Technology, Graz, (2004)
6. S. G. Shelby, *Delta-v as a measure of traffic conflict severity*, Indianapolis, USA, (2011)
7. G. Genta, L. Morello, F. Cavallino, *The Motor Car Past, Present and Future*, Springer (2014)
8. F. Kovačević, E. Smajlović, E. Džafić, N. Zdravković, *Evaluation of deformation work on vehicles in the analysis of traffic accidents*, (2016)
9. shorturl.at/fDTW2 [Accessed: April 2022]
10. <http://www.infotrend.hr/clanak/2009/5/3d-lasersko-skeniranje.38,785.html> [Accessed: April 2022]
11. <https://store.intelrealsense.com/buy-intel-realsense-lidar-camera-l515.html> [Accessed: April 2022]

Qualitative traffic indicators analysis and optimization model for traffic operations in urban zone

Gëzim HOXHA¹, Ramë LIKAJ¹ *, Astrit SALLAUKA³

¹Department of Traffic and Transport, Faculty of Mechanical Engineering, University of Pristina "Hasan Pristina," Pristina, Kosovo

²Department of Mechatronics, Faculty of Mechanical Engineering, University of Pristina "Hasan Pristina," Pristina, Kosovo

³Department of Traffic and Transport, Faculty of Mechanical Engineering, University of Pristina "Hasan Pristina," Pristina, Kosovo

* Corresponding author: Prof. dr. Rame Likaj, Faculty of Mechanical Engineering, University of Pristina "Hasan Pristina,"
* rame.likaj@uni-pr.edu

Received day month year; revised day month year; accepted day month year (use style Received dates, or Alt + Ctrl + R)

Abstract: The greater interest of people living in urban areas has been accompanied by an increase in demand for motorized movements and other forms of active movements in these areas. As a result, traffic problems have been increased extremely for these road users both in terms of the quality of movement and safety. This research is focused on identifying factors related to the quality of motorized and non-motorized movements in urban areas, a particular case study of the municipality of Fushe Kosova, and the design of a model for traffic optimization in urban areas. The current approach to prioritizing the solution of motorized traffic problems, especially in developing countries, has proved ineffective because, in the absence of addressing other mobility requirements (pedestrian, cyclist mobility), road users have been encouraged more to use this form of transport, leaving no room for other alternatives. The research aims to apply advanced methods for handling and managing traffic problems based on the principle of inclusion and building a model for optimizing traffic operation based on a specific case. The model is built using the programming language "Synchro," which enables the analysis, optimization, and simulation of all forms of transport: motorized traffic, movement of pedestrians and cyclists in the road network planned following these requirements. Obtained results show the advantages of using different forms of transport depending on the selected concept and the priority of certain forms of transport. The summary results and their comparison in terms of quality for different time intervals, including the different conditions of access to urban areas, are presented in tabular forms.

Keywords: LOS, DELAY, VEHICLE, MOVEMENTS, SIMULATION

1. Introduction

Growing size of cities and increasing population mobility has led to a surge in the number of vehicles on roads [1].

Traffic flow in heterogeneous conditions is highly complex and is difficult to predict the flow behavior on urban roads. Driver's comfort, convenience, traffic volume, lane width, grade type, geometric design, travel delay and safety are the major concerns on urban roads which are to be taken care [3]. LOS monitoring and traffic volume which represents quality transport has become indispensable. Traffic congestion and decreasing level of service has become major issues in most of the cities and results its impact on urban economy and its environment [2]. The route a vehicle takes through the network is dictated by a complex interaction between objectives of each vehicle and constraints imposed by the city on the roads. The objective of all vehicles movement with minimize of the time and without delay, it takes to travel from the source to the destination and it may re-route if the traffic conditions on their path deteriorate due to congestion [7]. An integrated city road network will enable faster, more comfortable and safer travel from source to destination [4].

In the concrete case of the research is included a part of urban road network of the F. Kosova. The layout of urban-local roads are in the form of a network, forming rectangular shapes of residential areas roads.

This urban area includes connecting roads "Dardania", "Hajrullah Zymi", "Shefki Kuleta", "Pajazit Islami", "Fehmi Lladrovci", "Tahir Zemaj", "Agron Rrahmani", and "Dedë Gjo Luli". There is no categorization of these roads, but from the function and the layout in blocks a categorization can be created, such as from geometrical dimensions, function of road (approach), and movement (figure.1.).

Geometric parameters of this part of the road, number of lines in available for movements, and approach of traffic in intersections result in not an appropriate LOS (level of service) and consequently, the quality of traffic operations is not acceptable (especially at peak hours). Also in terms of road safety [5], due to the high demands of motorization traffic and other traffic participants for access from the side parts, urban zone its characterized from unappropriated LOS.

The main local roads consist of two lanes, with two-directions of movement. There are sidewalks, which do not fulfill the needs of pedestrian movements, because in certain parts the width of sidewalks are less than the minimum required width. As result a number of car-pedestrian crash have been caused [5]. So the road safety in this urban zone is not in high level. The different mutual needs in local or urban areas and others impacts (vehicles parking needs, fulfilling of business requirements or commercial purposes), do that the urban mobility its unsustainable.



Fig.1. Urban zone of Fushe Kosova

Also in functional terms, traffic control intersections applied in some cases do not provide an acceptable level of service.

Road safety problems continue to be a concern for cyclists, without cycling lines and a lack of accommodation infrastructure to encourage people to use bicycles or other forms of active movement.

2. Methodology

For the purposes of the research, was used the automatic method of demand receiving for motorized traffic through cameras (figure 2), also is used the manual method and counting at characteristic points in the road network segments.

Data processing is realized by algorithm applying, which is preliminarily prepared in programming language "Python" [8]. By applying this algorithm, it is possible to count and categorize the traffic vehicles from video camera record, such as: car, van, minibus, bus, truck etc.



Fig.2. Traffic volume count from video- camera

For traffic quality indicators analysis, optimization, and derivation of the results of this research are used HCM mathematical model and software model "Synchro" which uses the same mathematical model (HCM 16 edition).

In the framework of traffic operation quality indicators, are analyzed some of important indicators such as: intersection capacity utilizes, v/s ratio, v/c ratio, progression factor, delay for vehicle, adjusted flow approach delay and approach LOS.

The obtained results then, are tested in the traffic simulation model built through the "Sim Traffic" software.

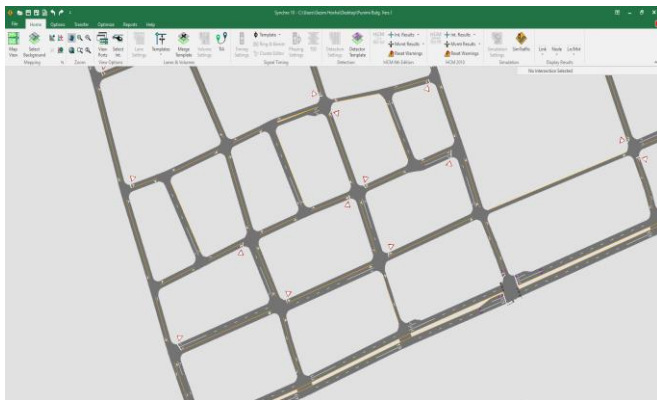


Fig. 3. "Synchro" model built for urban zone which was included in research

Within the road network of the urban area, have been selected the intersections with the main problems in the traffic operation, the biggest delays in the traffic and the poor quality of LOS (level of service), (fig. 4.).

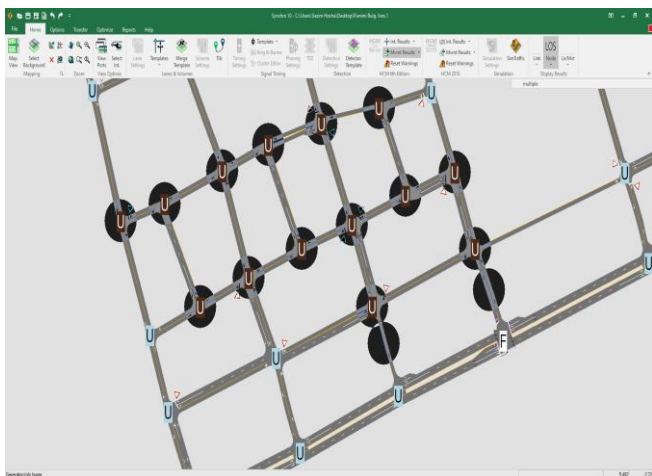


Fig.4. Selected intersections with the main problems in the traffic operation inside urban zone

3. Modeling, analysis, and optimization

By applying HCM mathematical model and Synchro model, has been analyzed: the quality of traffic operation inside the urban zone, especially at intersections, traffic problems, time delays, and general level of service. The left turns at intersections have been identified with greater delays and a very poor level of service. Even though according to the ICU calculation method, the capacities of some intersections have not been exceeded, in general in most intersections according to the HCM model, the level of service is unacceptable (in mainly intersections is F).

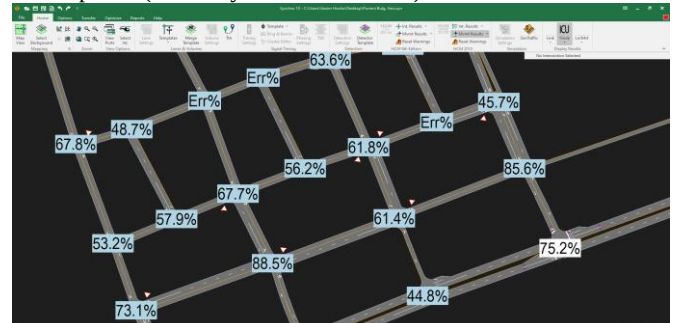


Fig.5. Intersections capacity utilize calculation

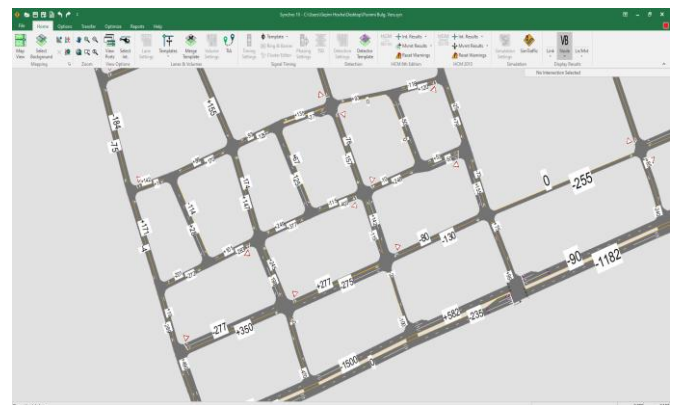
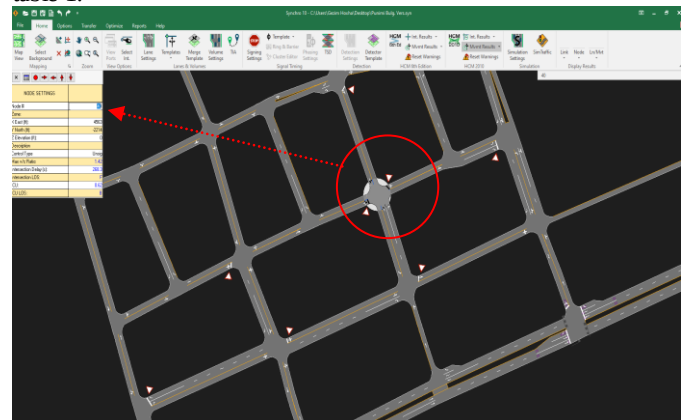


Fig.6. Intersections volume/balancing

The results about movements quality at the intersections with the biggest problems in the traffic operation (especially for left turns), are shown in the incorporated tables inside figure 7 as well as in table 1.



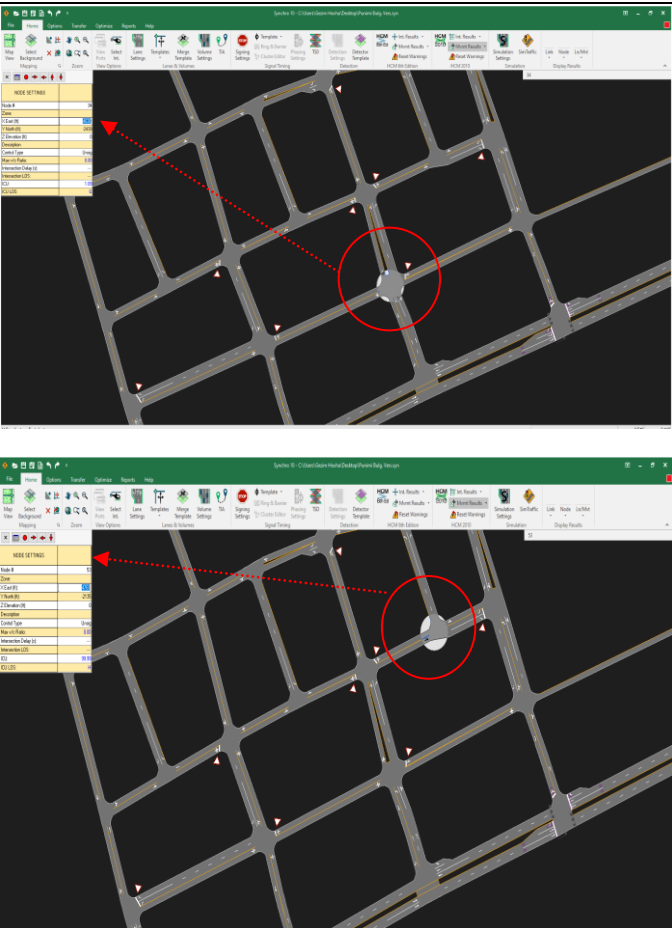


Fig.7. Intersections delays and LOS

Results obtained for one intersection inside road network of urban zone analyzed, are shown in table.1.

Table.1 HCM unsignalized intersection capacity analysis

												
Movement	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lane Configurations												
Traffic Volume (veh/h)	0	105	140	145	100	99	110	98	0	0	283	0
Future Volume (Veh/h)	0	105	140	145	100	99	110	98	0	0	283	0
Sign Control		Free			Free			Yield			Yield	
Grade		0%			0%			0%			0%	
Peak Hour Factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Hourly flow rate (vph)	0	105	140	145	100	99	110	98	0	0	283	0
Pedestrians												
Lane Width (ft)												
Walking Speed (ft/s)												
Percent Blockage												
Right turn flare (veh)												
Median type		None			None							
Median storage veh												
Upstream signal (ft)												
pX, platoon unblocked												
vC, conflicting volume	199			245			756	664	175	664	684	150
vC1, stage 1 conf vol												
vC2, stage 2 conf vol												
vCu, unblocked vol	199			245			756	664	175	664	684	150
tC, single (s)	4.1			4.1			7.1	6.5	6.2	7.1	6.5	6.2
tC, 2 stage (s)												
tF (s)	2.2			2.2			3.5	4.0	3.3	3.5	4.0	3.3
p0 queue free %	100			89			0	71	100	100	14	100
cM capacity (veh/h)	1373			1321			83	339	668	268	330	897
Direction_Lane #	EB 1	WB 1	NB 1	SB 1								
Volume Total	245	344	208	283								
Volume Left	0	145	110	0								
Volume Right	140	99	0	0								
eSH	1700	1321	129	330								
Volume to Capacity	0.14	0.11	1.61	0.86								
Queue Length 95th (ft)	0	9	1156	299								
Control Delay (s)	0.0	4.0	1204.5	69.9								
Lane LOS		A	F	F								
Approach Delay (s)	0.0	4.0	1204.5	69.9								
Approach LOS		F	F	F								

After traffic situation analysis through the above models and assessing of loads condition and traffic flow in the road network of Fushe Kosova, and also considering the high demand for active non-motorized traffic, it is proposed traffic flow reorganize in some "Dardania" neighborhood roads. This reorganize include transforming two-directions street into one-direction street.

So some of the roads within the urban area have been transform into one-way streets in order to eliminate left turns in conflict with other morotized movements at intersections. Referring to roads width inside the road network of "Dardania", through the transformation into a one-way road, it is possible to accommodate non-motorized movements such as pedestrians and bicycles, and also one part of these roads can be used for car longitudinal parking. Through the reorganization of motorized traffic, respectively transformation of some roads into neighborhood "Dardania" in roads with one-way traffic and giving priority to certain directions (following the principle of eliminating as many left turns as possible at intersections), are improved some traffic parameters such as: indicators of traffic quality (LOS, intersections delay etc.), intersections capacity, providing acomodation of active movements and, in general, is improved urban mobility inside this zone. Based on the above recommendations for measures application, through which it is possible to eliminate some left turns at some critical points in intersections, through the "Synchro" model has been realized the optimization of traffic parameters and have been obtained results which are shown in figure 9 and table 2.

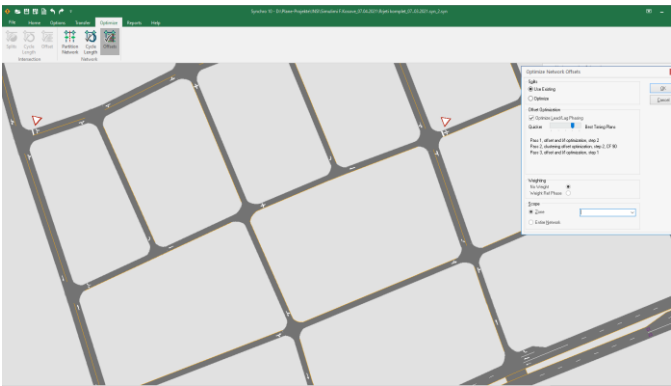
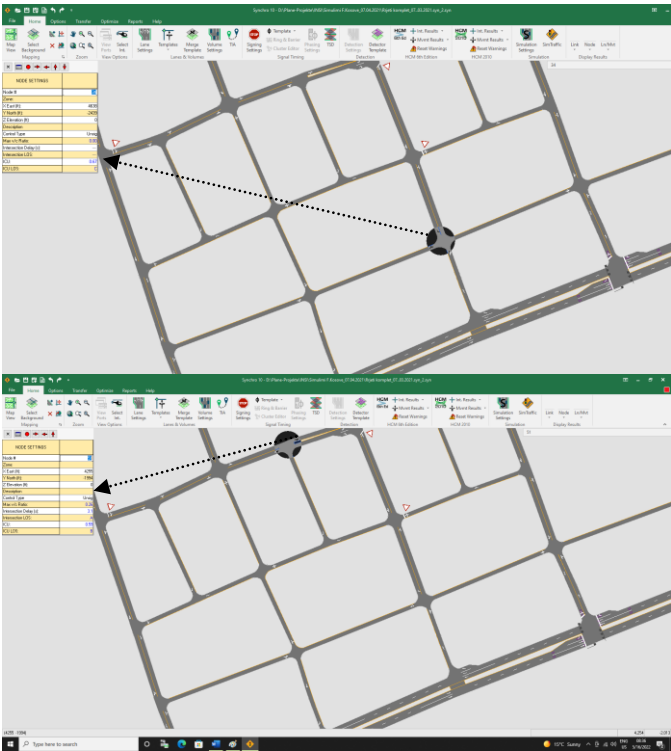


Fig.8. Model optimization



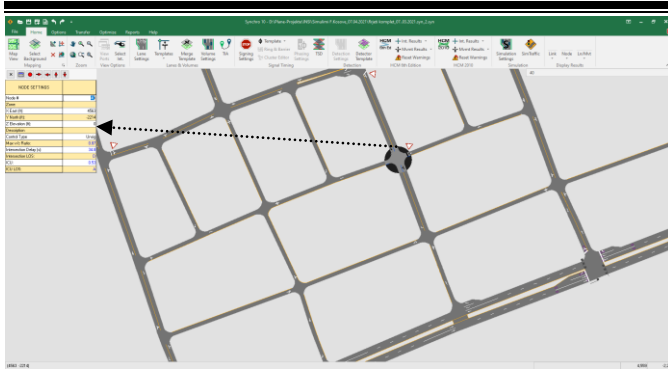


Fig.9. Intersections delays and LOS after traffic parameters optimization

After the optimization model was applied through the traffic reorganization inside the road network in urban area, for the same intersection for which the results of movements quality corresponded to the level of service F, they have passed to the service levels E and B (result for one intersection, table 2).

Table.2 HCM unsignalized intersection capacity analysis after traffic parameters optimization

	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Movement												
Lane Configurations												
Traffic Volume (veh/h)	0	250	50	0	0	0	0	75	110	250	0	28
Future Volume (veh/h)	0	250	50	0	0	0	0	75	110	250	0	28
Sign Control	Free			Free			Yield			Yield		
Grade	0%			0%			0%			0%		
Peak Hour Factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Hourly flow rate (vph)	0	250	50	0	0	0	0	75	110	250	0	28
Pedestrians												
Lane Width (ft)												
Walking Speed (ft/s)												
Percent Blockage												
Right turn flare (veh)												
Median type	None			None								
Median storage (veh)												
Upstream signal (ft)												
pK, platoon unblocked												
vC, conflicting volume	0			300			533	250	250	398	300	
vC1, stage 1 conf vol												
vC2, stage 2 conf vol												
vC3, unblocked vol	0			300			533	250	250	398	300	
IC, single (s)	4.1			4.1			7.1	6.5	6.2	7.1	6.5	6.1
IC, 2 stage (s)												
TF (s)	2.2			2.2			3.5	4.0	3.3	3.5	4.0	3.3
p0 queue free %	100			100			100	89	86	43	100	7
cM capacity (veh/h)	1623			1261			338	653	789	442	612	108
Direction, Lane #	EB 1	EB 2	NB 1	SB 1								
Volume Total	250	50	185	533								
Volume Left	0	0	0	250								
Volume Right	0	50	110	283								
ASH	1700	1700	727	844								
Volume to Capacity	0.15	0.03	0.25	0.83								
Queue Length 95th (ft)	0	0	25	296								
Control Delay (s)	0.0	0.0	11.6	35.3								
Lane LOS			B	E								
Approach Delay (s)	0.0		11.6	35.3								
Approach LOS			B	E								

From the model testing through the simulation, it is also concluded that at the intersections entrance can not be seen vehicle rows lengths and the time delays are acceptable (fig.10.).

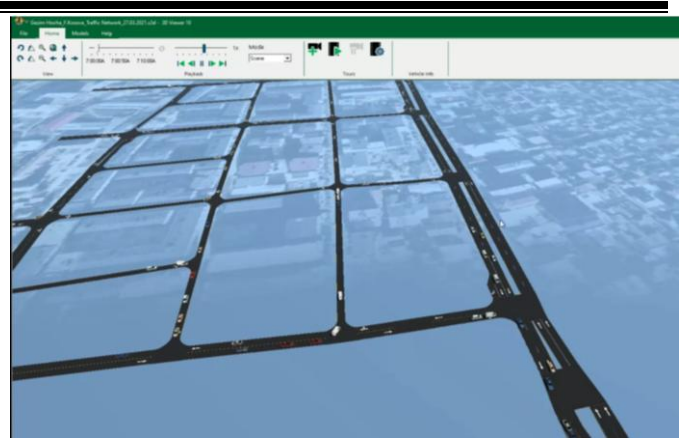
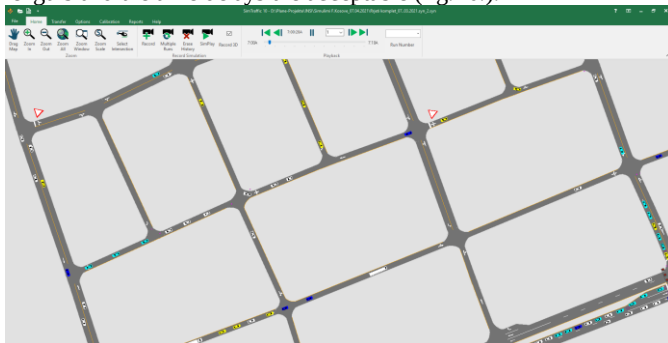


Fig.10. Model testing through simulation

Based on the obtained results related to traffic quality indicators, by traffic parameters optimizing and traffic reorganizing inside the area, transforming several two-way streets into one-way streets, eliminating left turns as much as possible, and the giving priority to certain directions at intersections: the improvement of the quality of traffic operation within this area has been achieved and, has increased possibility to accommodate non-motorized movements such as pedestrians and bicycles and, also for one part of these roads are increased possibilities for car longitudinal parking.

In line with these results, for responsible entities that manage with traffic problems in that area have been recommended to implement these measures in order to better manage traffic problems and increase the quality of urban life.

3. Conclusion

Referring to research results, we can conclude that through traffic parameters optimization and traffic reorganization of the inside urban zone, without the need for major infrastructural interventions, it is possible to improve the quality of motorized traffic and other movements within urban areas.

In concrete study case, by optimization model applying, through the traffic reorganization inside the road network in the urban area, for the same intersection for which the results of movements quality corresponded to the level of service F, they have passed to the service levels E and B.

Based on the obtained results related to traffic quality indicators, by traffic parameters optimizing and traffic reorganizing inside the urban area, transforming several two-way streets into one-way streets, eliminating left turns as much as possible, and the giving priority to certain directions at intersections: the improvement of the quality of traffic operation within this area has been achieved and, has increased possibility to accommodate non-motorized movements such as pedestrians and bicycles and, also for one part of these roads are increased possibilities for car longitudinal parking.

4. References

1. Y. Li, L. Yu, S. Tao, K. Chen, Multi-objective optimization of traffic signal timing for oversaturated intersection.
2. Patel and K Bhatt 2017 Level of service on different segment road: Review Int. Jr. Scientific Research in Science, Engineering and Technology vol. 3 pp. 451-454.
3. Abdulla-Al et. al. 2018 Estimating traffic volume to identify the level of service in manajor intersections of Rajshahi, Bangladesh Trends in Civil Engineering and its Architecture vol. 2 pp. 292-309.
4. Gezim Hoxha, Ahmet Shala and Rame Likaj, Vehicle Speed Determination in Case of Road Accident by Software Method and Comparing of Results with the Mathematical Model. Strojnicky časopis - Journal of Mechanical Engineering, 2017, Volume 67, No. 2. <https://doi.org/10.1515/scjme-2017-0017>.

5. Hoxha Gëzim, Shala Ahmet, Likaj Ramë and Bajrami Xhevahir. Mathematical Model for Velocity Calculation of Three Types of Vehicles in the Case of Pedestrian Crash. *Strojnícky casopis - Journal of Mechanical Engineering*, volume 68 (2018): Issue 3 (November 2018). <https://doi.org/10.2478/scjme2018-0029>.
6. Singh, Baalsrud Hauge, & Wiktorsson, 2021, Simulation-based participatory modelling in urban and production logistics: A review on advances and trends, *Sustainability* 2022, 14(1),17; <https://doi.org/10.3390/su14010017>.
7. Amita Singha, Jannicke Baalsrud Hauge, Utkarsh Upadhyay, Optimizing local and global objectives for sustainable mobility in urban areas, *Journal of Urban Mobility*, Elsevier, Volume 2, December 2022, <https://doi.org/10.1016/j.urbmob.2021.100012>.
8. Hoxha Gezim, Fandaj Arjanit, Quality of automatic traffic volume count from cameras and impact on traffic qualitative indicators, 2022.
9. Traffic Signal optimization and simulation modeling software, Syncho 11, 2019 Cubic ITS, Inc.
10. Traffic Data Analysis on Sathorn Road with Synchro Optimization and Traffic Simulation, [DOI:10.4186/ej.2017.21.6.57](https://doi.org/10.4186/ej.2017.21.6.57).
11. Sustainable Mobility Project 2.0, SMP2.0 Sustainable Mobility Indicators, 2nd ed. WBCSD, 2016.
12. Sustainable Mobility Project 2.0, Integrated Sustainable Mobility in Cities – A Practical Guide. WBCSD, 2016.

Traffic management system in the city of Rijeka

Siniša Vilke^{1*}, Frane Tadić², Borna Debelić³, Davor Mance⁴
 University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia^{1,2,3}
 University Of Rijeka, Faculty of Economics and Business⁴
 sinisa.vilke@uniri.hr

Abstract: This article analyzes examples of good traffic management practices in several European cities. The practices analyzed relate to providing more accurate information about public transport arrivals, optimizing demand for crosswalks, reducing congestion in urban areas, and reducing demand for trips to parking lots in the city center. Smart mobility projects such as CEKOM Connected Traffic create high-quality urban transport solutions and promote innovative, sustainable, clean and energy-efficient transport modes. The aim of this paper is to present the positive results of different traffic management methods that lead to better traffic flow, less congestion, lower primary energy consumption and less pollutant emissions.

The activities of this scientific research project are related to the development of innovative urban and multimodal solutions in the city of Rijeka. The primary outcome indicator will be a platform for aggregating data for urban mobility and transport decision making. The scope of the platform envisions more efficient use of public-private infrastructure, resources, and assets in the field of transport. In addition, it was necessary to accurately measure traffic, meteorological and environmental parameters in the city of Rijeka to protect the environment, increase safety and achieve sustainability of the transport system in the urban area.

As part of the research activities of the Connected Traffic project, a prototype solution for traffic simulations has been developed. The aim of the simulations is to show how the use of innovative methods in the context of intelligent solutions can manage traffic in urban areas. The purpose of the simulation is to test innovative scenarios and standard operating procedures for decision support.

Keywords: INTELLIGENT TRANSPORT SYSTEMS, URBAN TRAFFIC MANAGEMENT, CITY OF RIJEKA, URBAN MOBILITY, SUSTAINABLE TRANSPORT.

1. Introduction

Quality traffic management is one of the basic goals of the city authorities, considering that today it significantly affects the quality of life of citizens and at the same time represents a good basis for further economic growth. Traffic congestion is an obstacle to many urban areas around the world and requires the introduction of additional traffic management methods to address the problem. The conventional approach sought to eliminate the problem by additional road construction, but this option did not prove to be an effective solution. In the past few years, the issue has been solved by applying better management of existing capacities. Furthermore, such an approach requires additional tools that have proven to be an effective solution in traffic control through the examples of various cities.

The implementation of such systems meets certain criteria for increasing traffic safety, which are presented below in this paper through the above examples of good traffic management practices. Increased safety, reduction of air pollution, priority passage of various traffic participants, better control of urban areas and reduction of traffic congestion caused by road works or traffic accidents are some of the criteria as possible solutions to the problem of urban mobility in cities [1].

The paper "Review of Good Practices in the Introduction of Traffic Management Systems and Urban Mobility" provides a detailed review of examples of good practices in traffic management, while Chapter 3 of this paper provides a summary of the previously mentioned paper as a continuation of the analysis [1].

In addition to the examples of good practice, this paper seeks to present the transport system of the city of Rijeka and its further improvement of traffic management. Besides, the paper presents the City's involvement in Smart City Connected Traffic. Such a project aims to create an advanced information and communication system that will serve as decision support in urban mobility management. The purpose of the concept is to enable more efficient use of public-private infrastructure, resources, and property in the field of transport to protect the environment, increase safety, and achieve sustainability of the transport system in the urban area.

The development of innovative products and services expected after the completion of the CEKOM project will relate to the field of smart city technology and will be implemented through various pilot projects in the city of Rijeka, which will significantly affect the status of Rijeka as one of the smart cities in Croatia [2].

2. Urban traffic management

With the rapid development of cities, urbanization in the transport sector began to approach the limits of sustainability, especially in densely populated areas. However, the smooth flow of traffic is necessary for the quality of life, and at the same time affects the economic sector. Therefore, as the need for transport is constantly increasing, traffic jams, traffic accidents, reduced pedestrian safety and excessive environmental pollution are becoming more frequent.

Traffic management in urban areas where traffic flow is hampered by a large share of individual transport, inefficient traffic routes and inadequate urban plans, effectively solves traffic congestion problems and reduces the negative impact of traffic on the environment. Urban traffic management requires a balance between traffic throughput, safety and sustainability, which with a high population density, different modes of transport (pedestrians, cyclists, public transport, motorized vehicles) and a high proportion of shorter journeys, is quite a challenge [1]. The positive trend of rapid development of cities from year to year is becoming an increasing problem in most cities around the world. Urbanization of cities increasingly conditions mobility and brings traffic to the limit of sustainability, especially in densely populated places. Unhindered traffic is a major obstacle for the growing number of car users, but also for passive citizens in the role of pedestrians, cyclists and other users who are indirect participants in the city's transport network.

"A traffic control system generally uses traffic signals to control traffic flow at intersections and uses historical and real-time measured data to derive signal plans" [3]. Given the flexibility to adjust the measurement of traffic disturbances, the time control system can be characterized as a fixed and modern version. A fixed time control system, i.e., signal plans that are calculated offline and cannot be adjusted to real-time traffic flow disturbances are considered a conventional system, while the characteristics of a modern system are traffic response that can update signal plans according to current traffic data [3].

"Traffic control can be regarded as a multiagent application in which car-agents and traffic-light-agents need to coordinate with each other to optimize the traffic flow and avoid congestions" [4]. Agents' actions are mostly triggered by traffic information that is distributed in the environment on a practical and conceptual level. Therefore, abstractions from the environment naturally correspond to the scenario of the traffic control mechanism.

Effective traffic management requires ITS (Intelligent Transport Systems) instruments that have positive effects on increasing traffic flow, reducing pollution and increasing safety. For example, real-time information on environmentally friendly modes of transport such as walking, cycling and public transport can encourage citizens to use sustainable modes of transport more often, while optimizing traffic signal control can reduce fuel consumption and pollutant emissions. Research shows that the implementation of ITS in modern cities opens the potential to reduce greenhouse gas emissions by as much as 60 % by 2050 and the possibility of reducing the number of fossil fuel cars in urban transport by 50 % by 2030 [5].

3. Examples of traffic management systems in European cities

Examples of good traffic management practices include ways to address urban mobility in densely populated areas in terms of sustainability efficiency, safety and the environmental segment. The most common problems are traffic jams and accidents, problems with city parking and low pedestrian safety [1].

The purpose of introducing the RTPI system is reflected in greater reliability, more efficient system monitoring, reduction of congestion and decrease of external costs. Also, several European cities like Turin, Helsinki and London have introduced the RTPI system.

Displaying information about the arrival of buses at the station makes it much easier for public transport users to plan a trip. Access to real-time public transport arrival information is available at the station, it is also possible to access the information by entering the bus station number using the website or the DublinBus application. To facilitate the use of visually impaired people, the option of receiving information via SMS messages with the possibility of reading information by voice program has been introduced.

Automatic transmitters built into buses or GPS monitoring enable the operation of the bus arrival information system, while the software predicts the time of arrival at the next bus station. The control system then sends the data to the bus station notification screen, i.e., counting the minutes until the bus arrives. The vehicle location system is charged for data updating, which sends information at 30-second intervals, ensuring accuracy during the arrival time of the bus displayed on the notification screen. The National Transport Administration (NTA) monitors the reliability of the information to provide a better service [6].

The most common problems that can reduce the accuracy of information are operational segments such as [6]: technical difficulties, breaks, closed roads, mechanical problems and traffic congestion.

RTPI predicts the arrival of public transport using the location of the vehicle, so if the vehicle remains in traffic jams, the information on the arrival of public transport will be adjusted to current conditions.

Large crowds at pedestrian crossings are common in London, which is one of the largest cities in Europe. The implementation of the SCOOT system has contributed to a better and safer pedestrian crossing without the negative impact of slowing down road traffic [7].

The SCOOT pedestrian system is an effective way to manage traffic as it reduces congestion in densely populated areas, especially in pedestrian traffic. The system brings benefits in traffic management in terms of bus priority, traffic saturation control based on feedback, incident detection, online saturation measurement, vehicle emissions and pedestrian priority [8].

The collection of information is carried out at 3 890 distinct locations with the help of about 15 000 detectors that contribute to the optimization of traffic signals in favor of pedestrians, i.e., by optimizing the crossing time [9]. Furthermore, the SCOOT system uses cameras with the possibility of counting pedestrians at the pedestrian crossing, which solves the problem of uneven pedestrian traffic. Moreover, if the camera detects enough pedestrians, the

system will approve the road crossing, while in situations when there are no pedestrians at the pedestrian crossing or if a pedestrian presses the road crossing button and gives up, the system will not allow crossing the road [10].

Twenty years ago, Stockholm had major problems with traffic jams, especially in the city centre. Therefore, it was decided by the city authorities to introduce fees for entering vehicles in certain areas of the city. The charging of a fee for entering a certain part of the city by vehicle was introduced in Stockholm, given that such an example of good practice has already shown satisfactory results in London [11].

The introduction of a fee for vehicles entering certain zones has resulted in a reduction in CO₂ emissions by 14 % or 25 000 tons per year, or a reduction in transport by 22 % or 100 000 passengers per day with a reduction in travel time by 30 to 50 % [12].

Fees are charged using a system based on wireless RFID (Radio-frequency identification) technology. Furthermore, the system uses a toll charger and a traffic signal device in combination with an operating system developed by IBM [11].

Payment is made by contactless method or by using an electronic toll collection device that charges directly from the user account. Video cameras with an ANPR (Automatic number-plate recognition) system installed are also in use, enabling the record of the number of registration plates on the vehicle or the vehicle identification without a toll collection device to control the payment of the fee [11]. User billing options for the traffic saturation zone are as follows [13]:

- direct debit ("autogiro") - enables automatic debiting of the user's bank account or offers the possibility of combining with an electronic account,
- electronic invoice ("e-invoice") - the possibility of using Internet banking,
- payments - at the end of each month, the Swedish Transport Agency (Transportstyrelsen) sends a salary card to the owners of vehicles registered in Sweden.

Not all vehicles are required to pay a fee for passing through certain zones, e.g. [14]: ambulances, buses, diplomatic vehicles, people with disabilities, military vehicles, hybrid or electric vehicles, motorcycles and mopeds, and vehicles registered in other countries.

The introduction of toll zones has resulted in a reduction in traffic amount of about 20 %, which is equivalent to 100 000 passes per day through toll zones. The load on the main roads was also reduced by 30 – 50 %, which reduced the variability in travel time, while the emission of harmful gases was reduced by 10 – 14 %. Given the introduced fees, more than half of drivers decided to replace the passage of toll zones with alternative routes, while other drivers passed through the toll zone at the time when there is no toll.

In large urban areas, there is often a problem of finding a parking lot, so city authorities with "tools" for parking management are trying to reduce vehicle traffic or relieve the load on roads in certain areas. The parking management in the city of Vienna began in 1994, in addition to the long-term reduction of the need for parking. One of the primary reasons for the introduction was to provide many parking spaces with certain benefits for residents living near the parking lot. [15].

With the implementation of the parking management system, parking requirements have been reduced by 20-40%, while as an additional result, the behavior of traffic participants has changed. Furthermore, the introduction of the new system has led to higher demand for other forms of transport (mostly increased use of public transport, changing routes or shorter stays in certain areas), thus reducing traffic congestion and the negative impact on the environment.

The primary objectives of the parking space management system are [15]: reduction of car traffic and harmful impact on the environment, a better situation for parking and public transport (reduction of unauthorized parking), improved availability of cargo and delivery; renewed public space and improved road safety, higher revenues to improve urban transport, improved urban housing environment.

Parking management requires one form of transforming a part of the city district, i.e., turning one part into short-term parking zones. The price of parking increases from 1.20 to 2 euros per hour, which resulted in lower demand for parking.

Revenues from parking management are earmarked for further investment in the improvement of the Vienna transport system. The principle of parking management policy emphasizes that traffic costs are borne by traffic users and not by society.

To take full advantage of the implementation of the parking system in the city of Vienna, it is necessary to observe and apply a traffic management model such as: increase short-term parking fees, improve sufficient capacity and high-quality public transport, introduce affordable annual public transport tickets, development of "Park & Ride" system facilities, use of municipal residential garages, amendments to building regulations to reduce minimum parking requirements [15].

4. Traffic management in the city of Rijeka – project Connected Traffic

Taking practices of several European cities as an example, the use of the well-known ITS measure in this area provides remarkable results in increasing the overall efficiency of the road transport system. By using such services, cities create an efficient, safe, and sustainable transport system. They provide tools that enable efficient traffic management and have a positive impact on increasing traffic throughput, reducing pollution and increasing safety.

The City of Rijeka is currently using an automatic traffic management system which, with its technological capabilities, aims at optimal traffic management in the given conditions. The system is modular and easily adapts to new traffic conditions, and with its modern technology, it enables the control of traffic lights depending on the actual (current) traffic loading the traffic network. The system also enables upgrading of traffic subsystems from different areas of traffic, which significantly contributes to an additional increase of inflow within the city [16].

The current operation of the Automatic Traffic Management System (ATMS) has enabled: maximum utilization of the existing traffic network in the center of Rijeka, better flow of the main longitudinal directions - traffic corridors, direct 24-hour monitoring of traffic in the city center, automatic remote control of traffic lights, central reprogramming of traffic lights or individual traffic zones, immediate fault diagnosis and faster troubleshooting, automatic collection of traffic load data and savings in electricity consumption of about 51% compared to old traffic lights.

Through the participation of the City of Rijeka in the research and development activities of the project Connected Traffic, elements of the entire decision support system within smart cities are defined with the possibility of application in traffic. Solutions using cloud computing technologies will enable easier integration of electronic applications to improve communication and availability of public and commercial services for citizens and businesses [17].

4.1. Research and development activities

Through the research and development of the project activities of Connected Traffic, the aim is to create a platform for monitoring, coordinating, informing and managing all traffic in the urban environment, using the latest technologies and bringing together all the resources relevant to the insight of the necessary information related to the mobility of users. Particularly emphasis shall focus on

the environmental component and the encouragement of alternative innovative and intelligent forms of transport. The platform will be able to accept and process the planned amount of input data in real-time and expand it as needed for future requests and traffic increase [18].

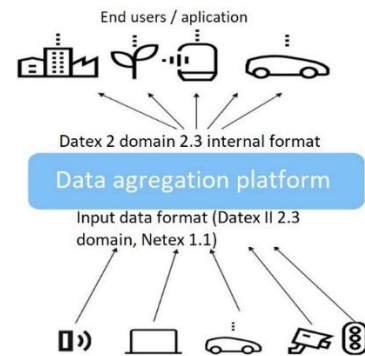


Figure 1. Data Aggregation Platform [18]

The basic functionality of the data aggregation platform is to transform, store and forward data received at the input, southbound interface from the senses and/or systems and/or applications to the southern interface according to the applications and systems that will use that data, as illustrated in Figure 1.

4.2. Technological concept

The existing results in this paper relate to all previously completed activities of the Connected Traffic project that the partners have successfully carried out. The preliminary activities were defining the scope of the project, which will serve as the produced platform for controlling, coordinating, informing, and managing the total traffic of the determined area. After the broader zone of the city of Rijeka was defined as the designed area of the project, all the existing documentation regarding urban and spatial planning and proposed solutions were examined.

By completing the questionnaires and conducting interviews with key stakeholders of the traffic of the wider urban area of the city of Rijeka, an analysis of the existing transport system and identification of the source and type of data has been performed. The need for analysis is implied by a large amount of data present in the transport system, which will grow further with the introduction and implementation of innovative technologies. Therefore, the collection of data is needed to create a basis for decision support. The main participants are direct representatives of road, maritime, air, and rail transport. In addition to them, other relevant participants of the transport system have a significant role in the elaboration, which also contributed significantly to the further definition of the project platform [2].

The most important and critical elements of the transport infrastructure for carrying out measurements to be carried out in the experimental phase of the project were identified. Consequently, the partners determined how the traffic, meteorological and environmental parameters will be measured for the traffic flow analysis. The measurement of traffic parameters will make it possible to obtain quantities showing the efficiency of the transport system and the level of service. By measuring meteorological parameters, traffic participants will always have an insight into current conditions that directly affect traffic safety, but also the current state of the roads. Furthermore, measuring ecological parameters will provide an overview of the real state of the environment of the urban area, i.e., insight into the level of

environmental pollution by CO₂ emissions. By further parameters elaboration, the project partners have identified and analyzed functional requirements for traffic, ecological and meteorological sensors that will meet the functionality of these parameters under different conditions. For the traffic parameters, the following sensors functional requirements are identified: identification and categorization of traffic modes, counting of traffic modes, simultaneous monitoring of all vehicles, identification of movement/routes for each vehicle, calculation of movement speed for the vehicle and pedestrian, calculation of standing time at the intersection for the vehicle and pedestrian, calculation of deceleration/acceleration for the vehicle, calculation of time of passing through the intersection, and advanced functionalities including detection of deviations and linking of information. Concerning meteorological parameters, the following functional requirements are determined: measurement of atmospheric conditions, temperature, humidity, dew point, air pressure, wind speed and direction, type, amount and intensity of precipitation and horizontal visibility. Ecological parameters are: particulate matter, volatile organic compounds, nitrogen oxide, carbon monoxide, sulfur dioxide and other greenhouse gases [2].

The project activity is analyzed in detail by exploring the technological concept of sharing and exchanging resources, infrastructure, and assets in the field of transport using the sharing economy platforms. This activity aims to achieve a more environmentally friendly transport system and to increase safety in the city area by using sharing concepts and benefits. Through the conducted interviews with end-users, as well as potential sharing economy stakeholders the possibilities of applying four concepts in the context of a smart city were defined: Centralized market supply, sharing public administration vehicles, encouraging multimodal transport and easier access to events.

Although all concepts are positively perceived by end-users and potential stakeholders through detailed evaluation and analysis, the concept which refers to easier approach to events was selected for further project activities development as the best evaluated and potential serviceable one.

Research and definition of advanced traffic analysis algorithms at intersections for detecting traffic anomalies and detecting incidents and dangerous situations have been made. Connected Traffic project partners have defined the technological concept of a data aggregation platform in the function of decision-making in urban and multimodal transport and urban mobility, which would make the platform a central place for sharing general traffic information to improve road safety. Intersections and traffic corridors where device tests would be carried out are also defined [18].

Furthermore, the identification of key and critical parts of infrastructure elements within urban agglomeration that were identified as locations suitable for testing and validation of solutions defined 4 final intersections out of the proposed 7 that will be equipped with video surveillance and video analytics. The final intersections and general representation of the system are shown in Figure 2. Anomaly detection of selected intersections consisting of video surveillance equipment with coordination for power supply and transmission of signals to the surveillance center, data storage servers, client computers, and associated video analytics software, and data processing, distribution and display software are shown. [18].

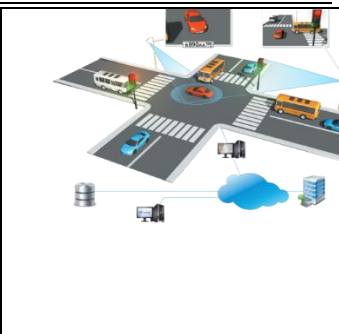
SELECTED INTERSECTIONS	
R24 – Strossmayerova – Tito square	
R26 – Žrtava fašizma – Fiumara	
R88 – Brajdica – Delta	
R29 – Jelačić square	

Figure 2. List of intersections and system views in principle [18]

Further s research and development steps of the project will focus on the design and future realization of a complete integrated system, including a center for management and monitoring, targeting services and organizations whose activity is related to transport, but also on the possibilities of a wider use of the system in the function of smart cities. A consequence of the system will be the possibility of increasing the level of safety in the protection of people and property through preventive procedures [17].

4.2.1. Testing innovative scenarios using simulation tool

As part of the research activities of the Connected Traffic project, a prototype solution for traffic simulations has been developed. The aim of the simulations is to show how the use of innovative methods in the context of intelligent solutions can manage traffic in urban areas. The purpose of the simulation is to test innovative scenarios and standard operating procedures for decision support.

The development of a simulation model forms the basis for a prototype simulation solution. Regarding the functionality and sustainability of the simulation model, the urban area and the wider administrative area of the city of Rijeka were considered. The process of creating a simulation model required the use of multi-layer traffic models integrating the macro, meso and micro levels of traffic simulations, the creation of a traffic network, i.e., the creation of a basic road network as well as the categorization of traffic and the regulation of intersections. Demand zones were then defined based on the travel needs of different social groups by population and trip purpose. In addition, OD matrices or definitions of travel demand for a given time interval were created.

Simulated scenarios are defined that describe traffic phenomena, trigger specific action strategies, and test key traffic parameters. They also serve as decision support for traffic management and precede the prototype traffic simulation solution. The defined traffic scenarios consist of regular and extraordinary events and traffic conditions.

SIMULATED SCENARIOS	REGULAR TRAFFIC EVENTS	Illegally parked vehicles Traffic condition Emergency intervention/Passage of VIP vehicles
	TRAFFIC CONDITIONS	High traffic density/Traffic congestion
	EXTRAORDINARY EVENTS	Manifestation-Road closure Roadworks-overregulation

Figure 3. Simulated scenarios [2]

The events and conditions usually require the initiation of certain actions that fall within the scope of traffic management and may exceed the authority of the traffic control unit or trigger the execution of certain automated procedures. Within the framework of the developed traffic simulations, it is possible to create various performance policies and analyze them in terms of selected traffic variables and traffic parameters to improve traffic efficiency and

increase the level of service. To create a simulation, six dynamic scenarios were created (Figure 3), representing a combination of traffic events with previously defined standard operating procedures.

5. Conclusion

Nowadays, choosing the optimal solution to the traffic problem of urban centers is not an easy task. We are witnessing excessive use of passenger vehicles in cities, which are facing increasingly unfavorable traffic situations every year. Finding an effective solution for most cities is still a great challenge. It is necessary to satisfy several segments such as bandwidth, safety, environmental awareness, economic cost-effectiveness, and many others.

As one of the output project indicators, a set of advanced analytical solutions is developing to support decision making in the field of urban traffic. The system defines new standard operating procedures that can be activated manually, automatically based on values received from the data aggregation platform, and automatically through direct notification. In addition, incident situations as well as regular and extraordinary traffic scenarios have been defined for the detailed development of prototypes for traffic simulations. Simulation models have been developed to test specific traffic scenarios resulting from defined standard operating procedures.

By applying the defined elements of the decision support system in transport, the efficiency of the Traffic Management Center in Rijeka will be improved. The platform will be tested in the function of the Center for Monitoring and Management of Integrated Traffic thus enable automatic distribution of data with easy availability to all interested users. There is no doubt that through the mentioned activities mentioned of the project Connected Traffic the city of Rijeka will certainly contribute significantly to its further development of the transport sector.

References

1. S. Vilke, F. Tadić, Review of Good Practices in the Introduction of Traffic Management Systems and Urban Mobility, *Journal of Maritime & Transportation Sciences*, 59, 95–113 (2020)
2. Ericsson Nikola Tesla, Apsolon, Alarm Automatika, Combis, Pomorski fakultet Rijeka, Rijeka Promet, Smart Sense, Project study-CEKOM Connected Traffic (2020)
3. R. Sha, Design and Performance Analysis of Urban Traffic Control Systems (2017) Available at: <https://core.ac.uk/download/pdf/154747275.pdf> [Accessed: 14 April 2021]
4. M. Camurri, M. Mamei, F. Zambonelli, Urban traffic control with Co-Fields, in *Lecture Notes in Computer Science* [including subseries *Lecture Notes in Artificial Intelligence* and *Lecture Notes in Bioinformatics*], Springer Verlag, pp. 239–253 (2007)
5. E. Jonkers, T. Gorris, Intelligent Transport Systems and traffic management in urban areas, *Civitas*, p. 36 (2015) Available at: https://civitas.eu/sites/default/files/civ_pol-not6_its_web.pdf [Accessed: 14 April 2021]
6. Dublin Bus, RTPI FAQs - Dublin Bus (2019) Available at: <https://www.dublinbus.ie/RTPI/RTPI-Help-Page/> [Accessed: 4 June 2020]
7. J. Davies, Using scoot multi-nodes to reduce pedestrian delay at dual crossings in Bristol, Bristol (2012) Available at: [http://www.jctconsultancy.co.uk/Symposium/Symposium2012/PapersForDownload/Jackie Davies Using SCOOT multi nodes to reduce pedestrian delay at dual crossings in Bristol.pdf](http://www.jctconsultancy.co.uk/Symposium/Symposium2012/PapersForDownload/Jackie%20Davies%20Using%20SCOOT%20multi%20nodes%20to%20reduce%20pedestrian%20delay%20at%20dual%20crossings%20in%20Bristol.pdf) [Accessed: 4 June 2020]
8. TRL, Pedestrian SCOOT Systems (2014) Available at: <https://trl.co.uk/projects/pedestrian-scoot-system> [Accessed: 4 June 2020]
9. Transport for London, TfL to launch world-leading trials of intelligent pedestrian technology to make crossing the road easier and safer (2014) Available at: <https://tfl.gov.uk/info-for/media/press-releases/2014/march/tfl-to-launch-world-leading-trials-of-intelligent-pedestrian-technology-to-make-crossing-the-road-easier-and-safer> [Accessed: 4 June 2020]
10. London to trial 'intelligent' pedestrian crossings (2014) Available at: <https://newatlas.com/pedestrian-scoot/31154/> [Accessed: 4 June 2020]
11. Road Traffic Technology, Stockholm Congestion Charge - Verdict Traffic (2003) Available at: <https://www.roadtraffic-technology.com/projects/stockholm-congestion/> [Accessed: 4 June 2020]
12. C40, Case Study, Stockholm to Introduce Congestion Charge - Trial Cut CO2 by 14 %, Traffic by 25 % (2011) Available at: https://www.c40.org/case_studies/stockholm-to-introduce-congestion-charge-trial-cut-co2-by-14-traffic-by-25 [Accessed: 4 June 2020]
13. Transportstyrelsen, Paying and notification of congestion tax (2020) Available at: <https://www.transportstyrelsen.se/en/road/Congestion-taxes-in-Stockholm-and-Goteborg/paying-the-congestion-tax/> [Accessed: 4 June 2020]
14. Stockholm's Congestion Pricing (2014) Available at: [https://www.toolsforchange.com/userfiles/Stockholm Congestion Pricing - FINAL 2014.pdf](https://www.toolsforchange.com/userfiles/Stockholm%20Congestion%20Pricing%20-%20FINAL%202014.pdf) [Accessed: 4 June 2020]
15. PUSH&PULL, Catalogue on Parking Management - Parking management and incentives as successful and proven strategies for energy-efficient urban transport (2015) Available at: https://www.eltis.org/sites/default/files/trainingmaterials/pp_pm_catalogue_01062015_final.pdf [Accessed: 27 June 2020]
16. Rijeka promet, Automatic traffic management (2021) Available at: https://www.rijekapromet.hr/hr/automatsko_upravljanje_prometom/5/16 [Accessed: 15 April 2020]
17. Smart City Connected Traffic (2020) Available at: <https://smart-ri.hr/smart-city-connected-traffic/> [Accessed: 11 April 2021]
18. Ericsson Nikola Tesla, Apsolon, Alarm Automatika, Combis, Pomorski fakultet Rijeka, Rijeka Promet, Smart Sense, Smart City.Connected Traffic: Report for TRL Phase 2 (2020)

Efficiency of intervention technologies for snow removal equipment on public roads

Sebastian Petru Boboc

Technical University "Gh. Asachi" of Iasi, Romania
bobocsebastian@gmail.com

Abstract: The activity of snow removal on public roads is of particular importance for ensuring road transport in winter and implicitly for maintaining a stable, predictable and efficient economic and social climate. The organization of road snow removal is usually done by the local public authorities, through the public road administrator, varying depending on the geographical and climatic location of the road site. In Romania, the snow removal activity is regulated by the "Regulation on preventing and combating snow on public roads", indicative AND 525-2013, developed by the National Company of National Highways and National Roads in Romania. The snow removal activity is usually performed on the basis of a service contract and is temporary, depending on the evolution of meteorological phenomena and climatic zones. The actions to prevent and combat the consequences of dangerous meteorological phenomena are carried out according to their intensity on the following phases, as follows: prevention of icing formation and its neutralization, spreading of anti-skid material and snow removal. The preventive spreading of the anti-skid material is recommended to be done first on the entry / exit arteries in / from the localities. The activity of mechanical cleaning of public roads (streets, bridges, alleys, roundabouts) of snow with blade machines is performed when the snow layer exceeds the thickness of 5 cm. The activity is carried out by successive passages, starting from the axis of the road to the curb, until the complete removal of the snow layer.

Keywords: ROAD, SNOW, WINTER, TRANSPORT, BLADE, CLEANING

1. Introduction

The activity of snow removal on public roads is of particular importance for ensuring road transport in winter and implicitly for maintaining a stable, predictable and efficient economic and social climate. Snow removal means the clearing or clearing of snow partially or over the entire width of the roadway or road platform, when the snow layer exceeds 15 cm. Removing snow is an act of clearing snow from the entire road platform, including snow cords that may favor another snowfall.

2. Results and discussion

The organization of road snow removal is usually done by the local public authorities, through the public road administrator, varying depending on the geographical and climatic location of the road site. In turn, the administrator of the public road may carry out the snow removal operations with the equipment from his own endowment or through a commercial company with which he concludes a service contract. Given the high cost of snow removal operations, determined by the costs of materials, labor, equipment and transportation, the organization of road snow removal must be carried out with maximum efficiency and minimum resources, at a quality necessary to ensure smooth traffic on public roads on during the winter, without endangering the safety of road users.

In Romania, snow removal is regulated by the "Regulation on preventing and combating snow on public roads"[1], indicative AND 525-2013, developed by the Romanian National Company of Motorways and National Roads. According to the above-mentioned regulations, the public road management units must prepare the snow removal in the summer, by drawing up the operational plans for the operation by July 15. These plans stipulate that the period of action against icing and snow must be between 20 October this year and 31 March next year. on November 1. Also the existence of a permanent stock of fuel necessary to ensure the operation of the machinery for at least 14 days must be ensured. Snow guard panels are installed until December 1 of each year.

Depending on their importance, the roads are divided into several levels of intervention. Level I includes highways, public roads with four lanes, public roads with two lanes, which connect the capital with the county-residence municipalities and those that connect the municipalities with the county-residence municipalities, public roads (national, county or communal), which ensures the connection with railway stations, ports, airports, border crossing points or which conditions the supply of important economic centers with raw materials, food or labor and the national roads that connect the tourist resorts. Level II includes the rest of the national roads that are part of technical class III and the county roads that ensure the connection with the communal centers. Level III includes

the rest of the public roads that must be maintained in a state of viability. Level IV comprises the sectors of public roads with low vehicle traffic.

Snow removal equipment groups are grouped on bases, subbases and support points. The main types of machinery and equipment used in snow removal are the following:

1) All-wheel drive machine, (Fig. 1) [2] equipped with:

- Snow blade with left-right rotation system and / or universal plow with variable geometry, with two movable blades that allow their positioning at different angles (sharp, obtuse, 180 degrees).
- snowblower (only in snowy areas);
- Spreader with a minimum capacity of 3 m³, mounted on the base machine chassis;
- Pre-wetting installation (only where there is a calcium chloride installation);
- Front mechanical brush;
- Cable / Rigid towbar for vehicles.

The equipment must be operated from desks mounted in the cab.



Fig. 1 All-wheel drive machine for snow removal.

2) High-capacity all-wheel drive tractor, equipped with:

- Snow blade, with left-right rotation system and / or universal plow with variable geometry, with two movable blades that allow their positioning at different angles (sharp, obtuse, 180 degrees).

3) Dumper truck with the formula of 4x4, 6x4 or 8x4 wheels and the payload of at least 10000 kg, equipped with:

- Blade with left-right rotation system;
- Spreader capacity min. 6 m³ optional pre-wetting system;
- Cable / Rigid towbar for vehicles.

The equipment must be operated from desks mounted in the cab.

4) Self-propelled snowblower all-wheel drive;

- 5) Backhoe loader with all-wheel drive, equipped with front bucket and / or plow;
- 6) Wheel loader;
- 7) Self-towing truck with a wheelbase of at least 8x4, equipped with special installations for towing and towing road trains:
 - Capstan;
 - Winch;
 - Special lifting arm.
- 8) Van with double cab, with special signaling panel for closing the traffic;
- 9) CaCl_2 preparation station;
- 10) Motor grader (Fig. 2) [3] with minimum engine power 160 hp;



Fig. 2 Motor grader.

- 11) Crane truck at least 40 tons.

The actions to prevent and combat the consequences of dangerous meteorological phenomena are carried out according to their intensity on the following phases, as follows: prevention of icing formation and its neutralization, spreading of anti-skid material and snow removal.

Road snow prevention is achieved by patrolling with equipment. This action takes place during quiet snowfalls or when the blizzards are light (wind strength below 30 km/h), and the scattered snow cannot immobilize the equipment on the road. If the wind force rises above that value and the snow is scattered in increasing numbers, the patrol action ceases and the machines withdraw, working to the base of residence or, if not possible, to the first locality on the route, in order to maintain traffic conditions for cars, buses or trucks that are covered in blizzard. The equipment used for patrolling is generally blade machines (graders, etc.) or vehicles with a metal blade mounted on the front (all-wheel drive multi-purpose machines, backhoe loaders, dump trucks, road tractors, etc.). Preferably, the blades will be fitted with rubber knives with metal insert. The most efficient patrol machine is the vehicle with adjustable blade, which is characterized by high blade mobility, high working speed and has the advantage that from a certain speed (usually over 30 km/h) throws snow from the side of the road platform. Their range is 30 - 50 km depending on the difficulties of the route, the frequency and abundance of snow.

The patrol formation is led by a technician and accompanied by a truck, which transports fuel and lubricants in sufficient quantities to ensure the supply of equipment on the road during the action. The equipment within the formation will work staggered in a transversal profile to include at least one traffic lane. Due to the fact that by patrolling the snow is collected in cords towards the edges of the platform, the equipment formations will be completed with turbo-milling equipment, which can also be used to remove the snow collected in front of the parapets. In areas with frequent blizzards, it is not allowed to keep the snow cords on the road platform, first releasing the part corresponding to the direction of the prevailing wind.

If two or more blade vehicles are assigned to a road sector, they can work independently, the start of the race will be delayed depending on the length of the road sector, the working speed and the abundance of snow. In this way a closed circuit can be achieved by ensuring the continuous presence of the machine on the road. Vehicles with blades will be equipped with a telephone or transceiver to ensure and inform operatively on road traffic conditions. The other means of patrol shown, which have low working speeds (10 - 20 km/h), but close, will be used in formations, on road sections less than 30 km long.

The choice of work teams is made taking into account the climatic character, the length of the road, the difficulties and the level of intervention of the respective road sector.

The control of icing and snow is done using both non-slip materials and chemical fluxes. The mixtures must be homogeneous and spread evenly over the road surface. The use of salt is effective only for temperatures on the road surface higher than -7°C . Pure salt should be used only on well-sealed clothing only with the approval of the public road administrator. Calcium chloride or equivalent chemical fluxes will be used for lower temperatures.

The preventive spreading of the anti-skid material is recommended to be done first on the entry / exit arteries in / from the localities [4]. The activity of mechanical cleaning of public roads (streets, bridges, alleys, roundabouts) of snow with blade machines is performed when the snow layer exceeds the thickness of 5 cm. The activity is carried out by successive passages, starting from the axis of the road to the curb, until the complete removal of the snow layer.

3. Conclusion

The road administrator must organize efficiently and properly both the information and control system on the condition of the roads and the way of preparation and operation during the winter. The management and coordination of the prevention and intervention activity for the control of road ice and snow must be carried out through coordination units established at central and territorial level by the public road administrator.

Given that the coordination of snow removal equipment and its judicious distribution of different road sections is of great importance, it is advisable to equip the equipment with GPS-type tracking systems to provide real-time access to detailed information on the location of the equipment, snow removal, route, speed, fuel consumption, number and duration of parking.

4. References

1. Compania Națională de Autostrăzi și Drumuri Naționale din România - S.A., "*Normativ privind prevenirea și combaterea înzăpezirii drumurilor publice*", indicativ AND 525-2013, Monitorul Oficial, **Partea I nr. 395**, 10 (2013)
2. Chasse_neige -- Haypo --
[https://fr.wikipedia.org/wiki/Fichier:Chasse_neige.jpg] -- [CC BY-SA 4.0]
3. 143h ploughing -- Smurrayinchester --
[https://commons.wikimedia.org/wiki/File:143h_ploughing.jpg] -- [CC BY-SA 3.0]
4. [Consiliul Local Oradea, Anexa la Hotărârea Consiliului Local nr. 583 - Proceduri de intervenție pentru activitatea de dezăpezire, prevenire și combatere a poleiului, din municipiul Oradea, 2 \(2012\)](#)

Segmentation of railway transport images using fuzzy logic

Balovsyak S.V.¹, Derevyanchuk O.V.¹, Derevianchuk Ya.V.², Tomash V.V.¹, Yarema S.V.¹

¹Physical, Technical and Computer Sciences Institute – Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine

²Department "Wagon Engineering and Product Quality" – Ukrainian State University of Railway Transport, Kharkov, Ukraine

Abstract: A prototype of a system for segmenting images of trains and wagons has been developed. Video cameras and specialized websites are used as the source of the original images. Median filtering of images and increase of their local contrast is carried out. The contours of the objects were calculated using the Sobel and Canny methods. Image segmentation is performed by the method of contour lines. As a result of the processing on the images of trains and wagons, meaningful areas (segments) were identified, for example, windows, headlights, etc. Detection of content areas of the object is performed using fuzzy membership functions. The hardware and software implementation of the computer system is made in Python using scipy and scikit-fuzzy libraries, the Google Colab cloud platform and Raspberry Pi 3B+ microcomputer.

KEYWORDS: DIGITAL VIDEO CAMERA, PYTHON, IMAGE SEGMENTATION, LOCAL CONTRAST, FUZZY LOGIC.

1. Introduction

The relevance of the study is due to the fact that currently there is a need to develop automatic tools for analyzing the state of rolling stock in railway transport, namely the state of trains and wagons [1, 2]. In many cases, information about trains and wagons is obtained using video cameras in the form of digital images. To simplify image processing, content areas (segments) are highlighted on them. For example, windows, headlights, homogeneous sections of walls, license plates, wheels, etc. are distinguished as segments of locomotives. Image segmentation [3, 4] greatly simplifies their further computer processing, in particular, determining the rotation, size and area of objects, object recognition. The scope of segmentation of images of trains and wagons is quite wide. Such image processing is currently used, for example, for technical diagnostics of objects, control of their position and speed of movement. The system of analysis of the condition of vehicles on the railway has much in common with other similar transport systems, in particular, for road transport. Such systems are the basis for the development of modern intelligent transport systems, in which information about vehicles is obtained from many sensors of different types.

However, the experimental images of trains and wagons contain a certain level of noise, the images have a heterogeneous background and contrast. This leads to the fact that a significant part of the segments is uninformative. Therefore, it is proposed to perform pre-processing of images before their segmentation by filtering noise and increasing local contrast. Experimental images do not always show unambiguous correspondence of segments to certain objects. For example, the image of a locomotive window can be divided into several segments. Therefore, the paper proposes to perform object detection on images based on their segments using fuzzy functions of segment belonging to a specific object (for example, to a window).

2. Algorithm for image processing and analysis

Based on the analysis of existing methods of reducing the noise level in images, increasing local contrast, contouring and segmentation [3, 4] developed an algorithm for processing and analyzing images in the form of an activity diagram [5] (Fig. 1). Reading of initial images is carried out both from video cameras, and from graphic files. The initial color image is read as a three-dimensional array $f_{RGB}(i, k, c)$, where $i = 0, \dots, M-1$; $k = 0, \dots, N-1$; M is image height in pixels, N is image width in pixels, $c = 0, \dots, 2$ – color channel number (Red, Green, Blue). Color f_{RGB} images are converted to grayscale (f_0 images).

Images f_0 are programmatically processed as rectangular matrices $f_0 = (f_0(i, k))$, where $i = 0, \dots, M-1$, $k = 0, \dots, N-1$.

As a result of the median filtering [3] of the image f_0 , the image f with reduced noise level is calculated.

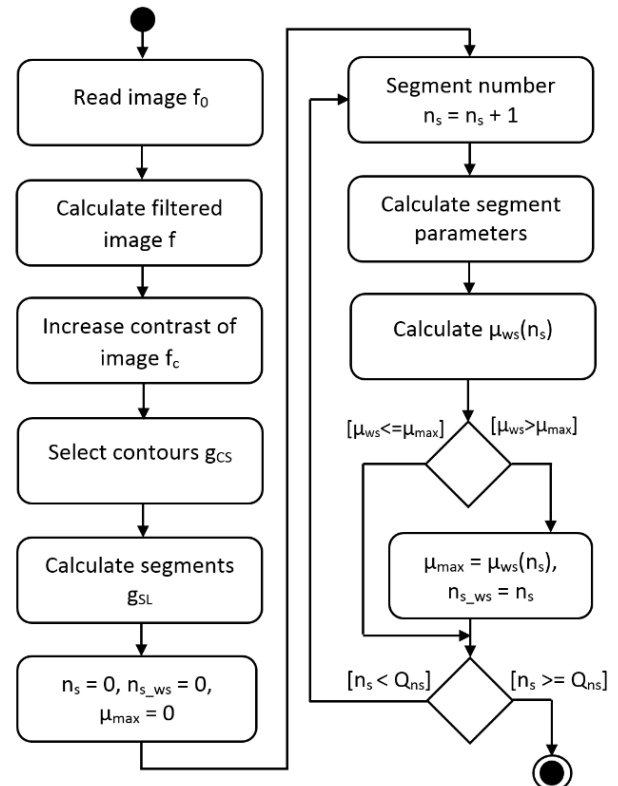


Fig. 1. Diagram of the activity of the image segmentation system of trains and wagons

Next, based on the filtered image f , the image f_c with high local contrast is calculated. Increasing the local contrast of images is performed by window processing of the image f using its envelope of brightness [6]. As a result of window image processing, its lower and upper envelope of brightness are first calculated, and then their smoothing is performed. Due to such smoothing distortions of the images which arise at increase in their local contrast decrease. In addition, by subtracting the lower envelope, it is possible to remove the inhomogeneous background of the image.

The sequence of increasing the local contrast is as follows. First, the dimensions of the local windows w of the image are determined, namely their height M_w and width N_w . By default, it is assumed that the windows w are square, i.e. $M_w = N_w$. When processing locally, windows w are formed for each pixel of the image f , while the pixel is placed in the center of the window at a distance of $M_{w2} = [M_w / 2]$ from its upper edge and at a distance of $N_{w2} = [N_w / 2]$ from its left edge. To prevent the windows from going beyond the image, the images f are expanded before their window processing, namely the expansion in all directions by half the height M_{w2} and half the width N_{w2} of the window. The result is an expanded image of f_c . A symmetric extension is used in this work, in which stripes of width N_{w2} are added to the left and right

images of f_e , and stripes of width M_{w2} are added at the top and bottom. The brightness of the bands is calculated as the brightness of the pixels of the image f , symmetrical about the boundary. Subsequently, the window processing of the extended image f_e is performed, in which the centers of the windows w are shifted by the value of M_{w2} from the edge of the image in height and by the value of N_{w2} in width. Due to this, the windows w do not go beyond the image and within each window you can correctly calculate its minimum and maximum value.

Within each window w , the minimum and maximum brightness values are calculated. The obtained values of local minima are written in the rectangular matrix of the lower envelope $f_{\min} = f_{\min}(i, k)$, where $i = 0, \dots, M-1$; $k = 0, \dots, N-1$. The obtained values of local maxima are written in the rectangular matrix of the upper envelope $f_{\max} = f_{\max}(i, k)$, where $i = 0, \dots, M-1$; $k = 0, \dots, N-1$.

To avoid distortion of brightness when increasing local contrast, the lower ($f_{\min}$) and upper ($f_{\max}$) brightness envelopes are filtered. Envelope filtration is performed by Gaussian filter with a standard deviation σ_{wG} (for example, $\sigma_{wG} = 16$) by convolving the envelopes ($f_{\min}$, $f_{\max}$) with the w_G core of the Gaussian filter (size $M_{wG} \times N_{wG}$ elements) according to the formulas:

$$f_{\min c}(i, k) = \sum_{m=1}^{M_{wG}} \sum_{n=1}^{N_{wG}} f_{\min}(i-m-m_c, k-n-n_c) \cdot w_G(m, n), \quad (1)$$

$$f_{\max c}(i, k) = \sum_{m=1}^{M_{wG}} \sum_{n=1}^{N_{wG}} f_{\max}(i-m-m_c, k-n-n_c) \cdot w_G(m, n), \quad (2)$$

where $f_{\min c} = f_{\min c}(i, k)$ is filtered lower envelope; $f_{\max c} = f_{\max c}(i, k)$ is filtered upper envelope; $i = 0, \dots, M-1$; $k = 0, \dots, N-1$; $m_c = (M_{wG2} + 1)$ is center of the filter core w_G in height; $n_c = (N_{wG2} + 1)$ is the center of the filter core w_G in width; M_{wG2} , N_{wG2} are whole parts of half the size of the core of the Gaussian filter w_G .

On the basis of envelopes ($f_{\min c}$, $f_{\max c}$) and the filtered image f the image-result f_c with the increased local contrast and the removed inhomogeneous background according to the formula is calculated

$$f_c(i, k) = \frac{f(i, k) - f_{\min c}(i, k)}{f_{\max c}(i, k) - f_{\min c}(i, k)}, \quad (3)$$

where $i = 0, \dots, M-1$; $k = 0, \dots, N-1$.

Formula (3) can also be written as

$$f_c(i, k) = (f(i, k) - f_{\min c}(i, k)) \cdot k_c(i, k), \quad (4)$$

where $k_c(i, k) = 1/(f_{\max c}(i, k) - f_{\min c}(i, k))$ are local contrast coefficients.

In order to prevent the appearance of artifacts (for example, parasitic contours) on the restored images f_c for the maximum values of the local contrast coefficients k_c set the limit k_{CMax} (for example, $k_{CMax} = 5$).

When processing color images, the pixel values of the high-contrast g_{RGB} color image are calculated by the formula

$$g_{RGB}(i, k, c) = \frac{f_c(i, k) \cdot f_{RGB}(i, k, c)}{f(i, k)}, \quad (5)$$

where $i = 0, \dots, M-1$; $k = 0, \dots, N-1$; $c = 0, \dots, 2$ are color channel number; f_{RGB} is the initial color image.

In high-contrast f_c images, g_{CS} contours are calculated by Sobel and Canny methods [3]. Sobel's method provides higher speed, and Kenny's method - higher accuracy.

According to the activity diagram (Fig. 1), after reading images from the video camera, noise filtering, contrast enhancement and contour selection, segmented g_{SL} images are calculated by method of contour lines [3, 4].

The obtained segment parameters are used to assess the condition of the studied objects (trains and wagons) and to detect objects (e.g. windows) using fuzzy membership functions [7]. In the cycle by segment number n_s , all segments with numbers from 1 to Q_{n_s} are traversed. Segments are selected by size. Segments with a height greater than $s_{iw, \min}$ (minimum segment height) and a width greater than $s_{kw, \min}$ (minimum segment width) are selected.

Selection of objects in the image (windshield, headlights, license plates, etc.) based on their segments is performed using fuzzy sets [7]. Based on the parameters of the segments (height,

width, center coordinates), the values of the fuzzy membership function μ_{ws} of the segment ns belonging to a certain object (for example, to a window) are calculated. The loop calculates the segment with the number $n_{s, ws}$ and the maximum value of the membership function μ_{max} , because such a segment best fits the desired object in the image (for example, a window). For all segments, their normalized height s_{iwN} is calculated and the corresponding values of the function of belonging of the segment $\mu_{wsh}(s_{iwN})$ to a certain object, taking into account its height. The values of membership functions are also calculated taking into account the normalized widths of the s_{kwN} segments and the coordinates of their centers (s_{icN} , s_{kcN}) in height and width. The value of the resulting membership function μ_{ws} of the segment with the number ns to the object, taking into account all the parameters of the segment (height, width, center coordinates in height and width) is defined as the product of the values of the corresponding membership functions:

$$\mu_{ws}(n_s) = \mu_{wsh}(s_{iwN}) \cdot \mu_{wsW}(s_{kwN}) \cdot \mu_{wsic}(s_{icN}) \cdot \mu_{wskc}(s_{kcN}). \quad (6)$$

By the maximum of the membership function $\mu_{ws}(n_s)$ calculates the segment number $n_{s, ws}$, which most fully belongs to the specified object. Other objects in the image are detected similarly.

3. Hardware and software implementation of image segmentation system

2.1. Hardware implementation of image segmentation system

The hardware (physical) model of the train and wagons image segmentation system is constructed using the UML deployment diagram (Fig. 2).

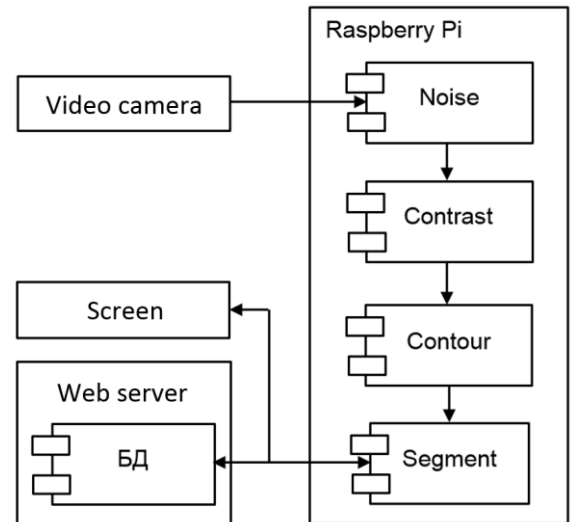


Fig. 2. Physical model of the system of segmentation of images of trains and wagons

The deployment diagram shows the location of system components at system nodes. According to the physical model, the initial images are read from a video camera (connected to a Raspberry Pi 3B +) and processed using a Raspberry Pi 3B + microcomputer [8]. The «Noise» software module reduces noise by filtering, the «Contrast» module increases the local contrast of the image, and the «Contour» module calculates image contours (which are then used as segment boundaries). The «Segment» module segmented images and calculated segment parameters. The «Detection» module detects objects using fuzzy membership functions. The received data is also transmitted to a remote web server for further analysis and displayed on the screen.

The hardware part of the prototype of the trains and wagons images segmentation system consists of a Raspberry Pi3B +

microcomputer [8], a digital CSI video camera or a USB video camera (Fig. 3).

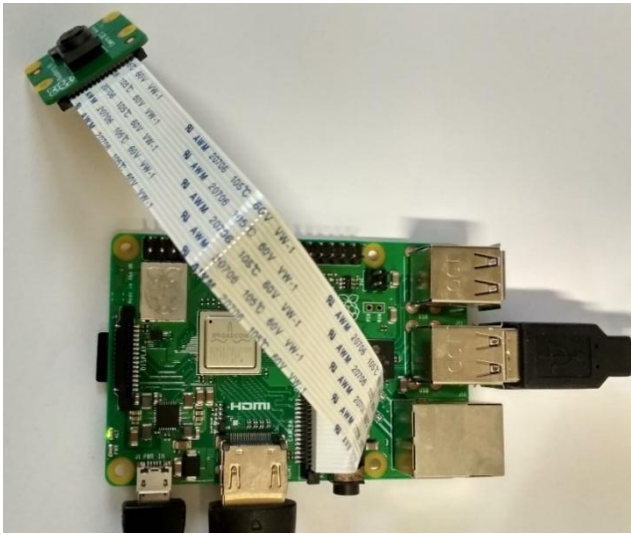


Fig. 3. Photo of the Raspberry Pi 3 Model B + microcomputer

2.2. Software implementation of image segmentation system

The software part of the trains and wagons images segmentation system was developed in Python first by Google Colab cloud service (in the Jupyter Notebook) [9], and then transferred to the hardware platform of the Raspberry Pi3B + microcomputer (with Raspbian operating system installed) in the development environment Thonny Python IDE [10]. The program uses libraries such as scipy, numpy, matplotlib, opencv, scikit-fuzzy.

The initial (input) data for the developed program are digital images read from a video camera or from graphic files (images of trains, locomotives, wagons). The program supports reading images of basic graphic formats (.bmp, .jpg, .tiff).

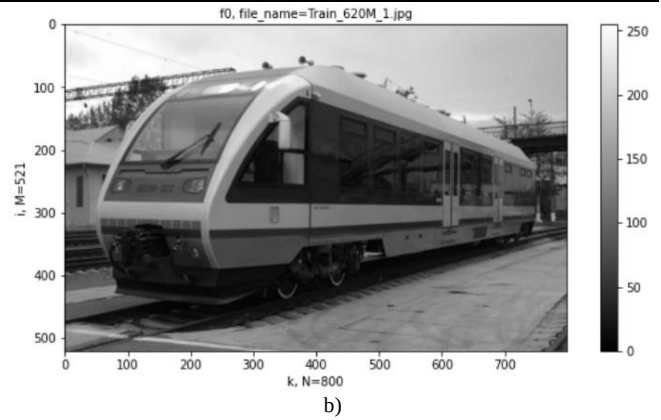
The source data (results) of the program are image segments and coordinates of rectangles that correspond to the content areas of objects (for example, windows, license plates).

4. Test results of image segmentation system

Let's consider an example of segmentation of the image of a locomotive by means of the developed system. First, the initial color image is read from the graphic file (Fig. 4a) and the original image in shades of gray is calculated (Fig. 4b).



a)



b)

Fig. 4. Initial color image f_{RGB} (a) and image f_0 in shades of gray (b) [2]

As a result of the median filtering of the image f_0 in shades of gray (Fig. 4b), the image f is obtained with a reduced noise level. Based on the image f , the image f_c (3) with increased local contrast is calculated (Fig. 5).

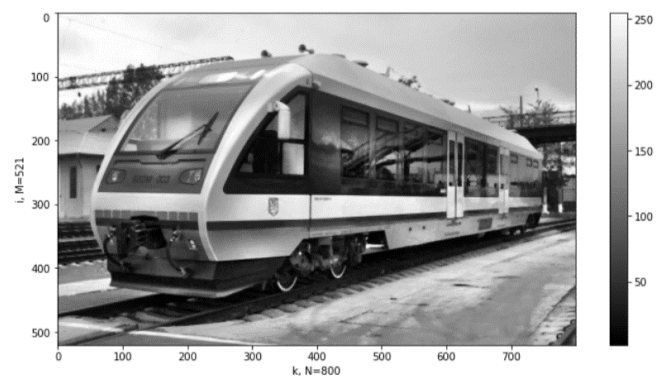


Fig. 5. Image f_c with high local contrast, obtained on the basis of the image f

The g_{CS} contours were calculated by the Sobel method (Fig. 6).

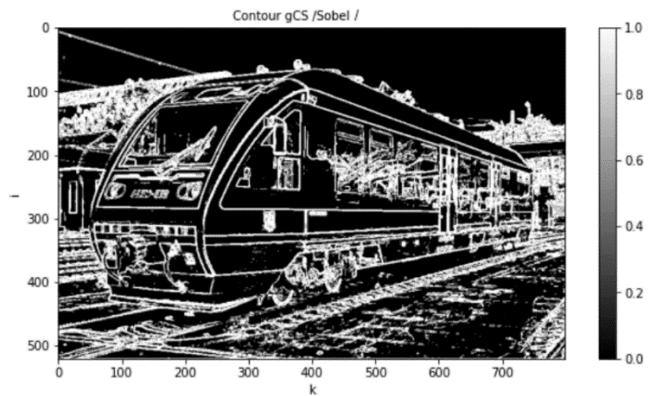


Fig. 6. Contours of g_{CS} images obtained on the basis of f_c images by Sobel method

Image segmentation is performed based on their g_{CS} contours, which highlight the boundaries of the segments. The numbers of the received segments are written in the g_{SL} array. Segments with a height greater than s_{iw_min} (minimum segment height, $s_{iw_min} = 30$) and a width greater than s_{kw_min} (minimum segment width, $s_{kw_min} = 30$) were selected. As a result, the most significant segments in the form of g_{SL2} images were selected (Fig. 7).

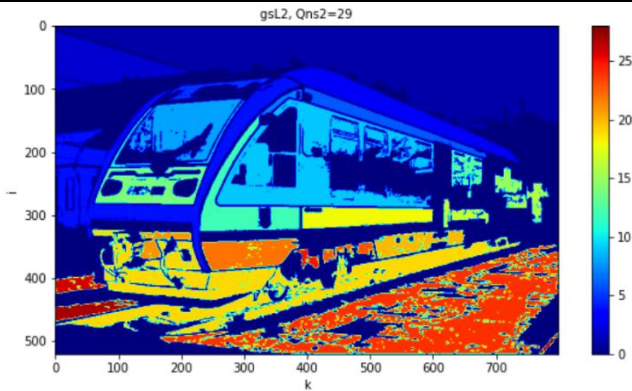


Fig. 7. Segmented g_{sl2} image after segment selection; Q_{ns2} is number of segments

The windshield was detected using fuzzy sets. Based on the analysis of the parameters of the segments corresponding to the windshield, the parameters of fuzzy triangular membership functions were determined (Fig. 8). For each segment with the number ns its normalized height s_{iwN} (for the image height of 1000 pixels) was determined and the corresponding value of the function of belonging of the segment $\mu_{wsh}(s_{iwN})$ to the windshield was found taking into account its height (Fig. 8).

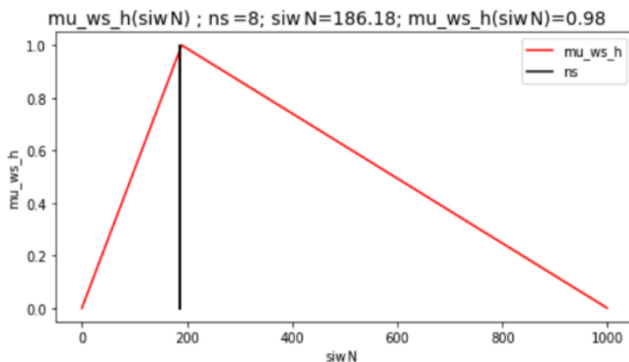


Fig. 8. Membership functions of fuzzy sets, which describe the belonging of the segment with the number ns to the windshield depending on the normalized height of the segment s_{iwN}

Similarly, the values of membership functions are determined taking into account the normalized width of the segment s_{kwN} and the coordinates of its center (s_{icN} , s_{kcN}) in height and width. The value of the resulting function of belonging of the segment with the number ns to the windshield, taking into account all the parameters of the segment is determined by formula (6). The maximum of the membership function $\mu_{ws}(ns)$ calculates the segment number $n_{s_{ws}}$, which most fully belongs to the windshield (Fig. 9). The result is correct.

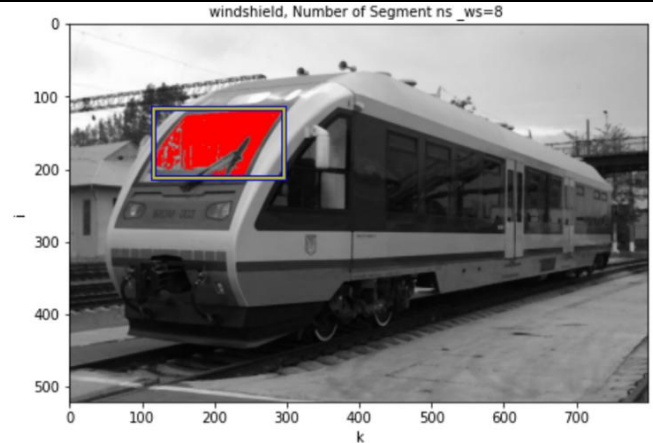


Fig. 9. The result of windshield detection

The results of windshield detection for other images of locomotives are also correct.

Headlights and license plates are similarly detected in the images.

5. Conclusions

1. The prototype of the system of images segmentation of trains and wagons is developed. The activity diagram and physical model of the system are developed.
2. Created a program in Python for noise filtering, increasing local contrast, contouring and image segmentation.
3. Fuzzy logic is used to detect train components in images.
4. Hardware and software implementation of the system in Python using Google Colab cloud platform and Raspberry Pi 3B + microcomputer is performed.
5. Processing of test images showed high accuracy of detection of components of trains on their images.

6. References

1. Roads Service. URL: <https://www.roadsni.gov.uk>.
2. Ukrzaliznytsia. URL: https://www.uz.gov.ua/press_center/photogallery/gallery-265193/.
3. Russ J.C. The Image Processing. Handbook. Abingdon-on-Thames, Taylor & Francis Group, 2011, 885 p.
4. Image Segmentation. URL: https://scikit-image.org/docs/dev/user_guide/tutorial_segmentation.html.
5. The Unified Modeling Language. URL: <http://www.uml-diagrams.org>.
6. Balovsyak S.V., Kravchenko H.O., Derevyanchuk O.V., Kroitor O.P., Tomash V.V. Computer system for increasing the local contrast of railway transport images. – Proc. SPIE, Fifteenth International Conference on Correlation Optics, V. 12126, 2021, P. 121261E1-7.
7. Hooda D., Raich V. Fuzzy Logic Models and Fuzzy Control. An Introduction. Alpha Science International Ltd., Oxford, U.K., 2017. 408 p.
8. Raspberry Pi Compute Module 3+. URL: <https://datasheets.raspberrypi.com/cm/cm3-plus-datasheet.pdf>.
9. Google Colab. URL: <https://colab.research.google.com>.
10. Thonny. Python IDE. URL: <https://thonny.org>.

Measures for improving pavements roughness

Razvan Buliga

Gheorghe Asachi Technical University of Iasi, Faculty of Civil Engineering and Building Services, Iasi, Romania
razvan.buliga@gmail.com

Abstract: The occurrence of road accidents due to a pavement surface with inadequate roughness is an alarming issue. This problem involves not only the design, construction and maintenance of road pavements, but also the properties of the materials used in the asphalt mixes, traffic volume and vehicle speed, as well as tire characteristics, human factors, environmental conditions and many other contributing elements. As a result, there is a growing awareness of these problems and adequate measures have to be taken by road administrations in order to improve traffic safety. For the design, construction and maintenance of a modern road network, along with strength and sustainability, skid resistance has become an integral part of a safe and efficient road system. With the increase in traffic speed and volume, the road pavements built today must have initial and continuous qualities of high skid resistance. It is a well-known fact that the pavements skid resistance is reduced primarily by mechanical wear and polishing due to traffic action; however, to what extent the friction characteristics are diminished and the other causes and effects of this reduction are problems that road engineers have to face. Although the automotive and tire industries have contributed greatly to the research and development of skid-resistant road pavements, it is quite obvious that most of the improvements will go to pavements. In the following, the paper will focus on establishing the roughness criteria that can be applied from the early stages of the construction of a road infrastructure, by selecting those materials and techniques that lead to a high level of roughness and thus traffic safety. Also, the paper presents the results of recent experimental studies undertaken to determine the road roughness, using the microtexture as well as macrotexture criteria, conducted in Romania on the national roads DN 2 km 212 + 000 and DN 15 km 290 + 870.

Keywords: PAVEMENTS, ROUGHNESS, MACROTEXTURE, MICROTEXTURE, SKID RESISTENCE.

1. Introduction

Globally, interest in improving road safety has long since begun. In 1969, the Highway Research Center published a study regarding skid resistance of road pavements conducted in four states. The Office of Public Roads, along with state highways in Colorado, Wyoming, Utah, and New Mexico, also performed specific tests to determine the importance of surface characteristics in increasing the road safety. All these tests have been performed with a special trailer belonging to the Public Roads Office, following ASTM criteria and procedures. 979 tests have been conducted on a variety of pavement types and highway systems. Due to its open-textured surface, seals using a bituminous mixture made in the bituminous plant mix offered the highest coefficients of skid resistance; followed by chip seals, asphalt concrete and cement concrete. In the case of chip seals, as in all other areas, the annual average daily traffic and the age of the road pavement have proven to be the most influential factors [1].

A large difference in skid resistance between inner and outer lanes on four-lane roads has been frequently observed in the four states. The study concluded that the use of bituminous plant mix seals is the best way available to ensure a high quality, non-skid surface, not only as a strategy to improve existing surfaces, but also in the construction of new roads [1]. Based on these results, adequate roughness measures need to be analyzed and implemented from the design phase of road pavements.

The relationship between accidents frequency and pavement texture of a road surface is often overlooked, but this is an important factor in road safety. Road pavement with high skid resistance properties can be a significant factor in reducing the likelihood of an accident. Skid resistance is related to both the properties of the vehicle tire and the road surface and can be affected by the volume and composition of traffic, the depth and pattern of the tire tread, the temperature of the pavement, the presence of water (rain) and other driving conditions [2].

The pavement surface must ensure an adequate level of friction at the tire-road interface for the safe operation of vehicles in normal weather conditions. The texture of the road surface is defined by two parameters: microtexture and macrotexture.

Microtexture is fine-grained granulation (≤ 1 mm deep) on the surfaces of coarse aggregates. The microtexture is responsible for the direct contact between the tire and the road, thus providing resistance to skidding.

Macrotexture is the large-scale roughness that exists on the road surface due to the arrangement of the aggregates and controls the drainage capacity of the pavement [2].

The combination of microtexture and macrotexture, together with the way these textures change due to traffic and climatic factors, form the general drag resistance of a particular road. Damage to the road surface (smoothing or sanding), together with the accumulation of surface water in the form of rain, snow or ice, can lead to inadequate skid resistance. Inadequate skid resistance can lead to a higher incidence of road accidents. There is currently no agreement on the standards that can be used to optimize skid resistance, despite a significant amount of research.

Skid resistance represent the opposing force which is developed in the tire-road contact area [2]. This resistance, also called skid friction, is a significant component of traffic safety, as it is essential in maintaining the control of the vehicle and decreasing stopping distances in urgent braking situations.

Skid resistance has two major elements: adhesion and the so-called hysteresis phenomenon [3]. Adhesion is the result of the shearing of the molecular bonds formed when the rubber tire is pressed in close contact with road pavement aggregates. Hysteresis results from the dissipation of energy when the tire rubber is deformed when passing over the asperities of a rough pavement [2].

These two components of skid resistance are linked, respectively, to the two key properties of asphalt road surfaces, namely microtexture and macrotexture.

Previous studies agree that both the microtexture and the macrotexture of a pavement have an important influence on the pavement skid resistance.

Microtexture deals with irregularities on the aggregates surfaces that affect adhesion. The size of the microtexture depends on the initial roughness on the surface of the aggregate and the ability of the aggregate to retain this roughness against the polishing action of the traffic [4]. Consequently, microtexture is an aggregate-related property that can be controlled by selecting aggregates with desirable polish strength characteristics. The evaluation of the aggregates regarding their polishing behavior can be performed using laboratory testing procedures developed for this purpose. Microtexture and adhesion contribute to skid resistance at all speeds and is the predominant influence on skid resistance at speeds below 30 mph [5].

Macrotexture deals with the larger irregularities on the road pavement that affect the hysteresis. These are associated with voids between the constituent aggregates in the wearing course. The size

of this component will depend on some factors, including the size, shape and particle size of aggregates used in road construction, the specific construction techniques used in laying the wearing course [6]. Macrotexture is also significant in providing drainage channels during the tire-surface interaction, thus reducing hydroplaning. This phenomenon is the loss of tire traction caused by a film of water separating the tire from the pavement surface [2].

The main purpose of determining skid resistance is for quality control during construction and for subsequent road management. Road friction values are used in road network studies, evaluation of intervention strategies, criteria for new construction, accident investigations and winter road maintenance, among other purposes. Skid resistance values are also taken when potential road safety problems are observed and when the road surface has recently been repaired to correct friction problems [2].

Historically, macrotexture measurement has been obtained by a volumetric technique [7]. This basic method consists of spreading a known volume of material (sand, glass beads or grease) on the road and measuring the covered area. Dividing the volume by area provides the depth of macrotexture (average texture depth, MTD).

The current ASTM standard [7] for macrotexture measurement requires the use of glass beads instead of sand. The material has been changed for two reasons: glass beads spread more evenly than irregularly shaped sand, and very low yields are usually obtained when sandbags are screened.

Good skid resistance on flexible pavement surfaces could be achieved by controlling both microtexture and macrotexture. In the case of microtexture, it largely depends on the composition of the aggregates. Good skid resistance must be achieved by selecting quality, sand-resistant aggregates. An ideal aggregate for the asphalt mixture should be composed of hard, coarse, angular minerals, well glued in a softer matrix, so that a gradual differential wear occurs [2].

The macrotexture will depend on the specific type of mixture, the particle size of the aggregate (dense or porous mixture) and the stability of the mixture. There are two types of road pavements that can be used to achieve a high level of macrotexture in new roads: open graded asphalt concrete - for flexible pavements and textured surface for rigid pavements (PCC). However, the reshaping of the existing pavement can be achieved by overlapping open graded asphalt concrete, grooving, cold milling and seal layers [6].

2. Elements that affect the skid resistance

Skid resistance is generally considered a problem when the road is wet, as it is known that dry road pavements provide sufficient skid resistance to stop vehicles. Thus, previous test procedures and safety studies related to skidding have focused on wet road conditions. Vehicles traveling at low speeds on wet roads develop full hysteretic frictional force on the surface. At low speeds, surface water is squeezed from under the vehicle's tire, keeping it in full contact with the surface. However, the skid resistance properties deteriorate as the vehicle speed increases.

As mentioned above, maintaining good skid resistance is very important in wet conditions for traffic safety. Research efforts have been made to identify improved methods of draining rainwater from the surface of multi-lane roads and to develop guidelines for their implementation. Drainage plays an important role in mitigating hydroplaning and splashing and spraying, as these two issues tend to depend on the thickness of the water film on the road.

Ways to reduce the thickness of the water film is important for the safety of drivers, avoiding dangerous situations. Some of the techniques developed to reduce the water film are: alteration of road geometry; installation of drainage accessories, use of permeable or open graded asphalt mixtures, Portland Cement Concrete grooves and improving the surface texture by selecting and designing the bituminous mixture.

Other means of reducing the flow of surface water on the road are porous asphalt concrete pavements. These surfaces also provide a means of draining water under the tire, thus reducing the potential for hydroplaning.

“Asphalt surfaces with internal drainage” is another technique to reduce the water film on road surfaces, by using asphalt mixtures with discontinuous particle size distribution. This internally drained road pavement has the potential to minimize the water film and hydroplaning and can reduce the thickness of the water film by allowing internal drainage, which effectively reduces the amount of water to be drained on road surfaces. Most research reports highlight the internal drainage aspects of porous asphalt mixtures. However, the improved surface texture it provides may be of equal or greater importance than the internal drainage it provides [2].

Porous mixtures have been widely used in Europe. These mixtures are usually placed with binders that are modified with fibers or polymers. These mixtures contain about 20% air voids, which is significantly higher than the mixtures used in the U.S. Road surfaces with porous mixtures also offer high values of skid resistance and help to remove water from the road surface.

The effectiveness of porous mixtures can be improved if drainage systems are installed inside pavement layers. Continuous material drainage systems that can be placed either transversely or longitudinally with the direction of flow [8].

Although porous asphalt mixtures are generally accepted as useful in reducing hydroplaning, their performance has been unsatisfactory in many states, as several states have completely eliminated their use. Instead, they are widely used on motorways in Europe, especially in France and the Netherlands [9].

Another method for water film control is to maximize the texture of the surface. The reduction in the water film is directly proportional to the increase in macrotexture. Because porous asphalt surfaces are usually made of relatively coarse aggregates with a grain size curve with a minimum amount of sand-sized material, they generally produce high levels of macrotexture. The macrotexture, in other asphalt surfaces, is also controlled by the granulometric curve of the aggregate.

3. Laboratory testing. The asphalt mix design

Various experiments have been carried out which included different components of the asphalt mixture, such as the types of binders and aggregates, with different particle sizes, the percentage of air void and the binder content and the measurement effect of these variables on the macrotexture.

Variations in microtexture and macrotexture were studied by manipulating the selected variables in the design of the asphalt mixture. Asphalt mixes are designed to meet specific volumetric and stability requirements by manipulating a number of variables. The controlled variables that could affect microtexture and macrotexture were the following:

- The maximum nominal size of the unit;
- Type of aggregates;
- Percentage of air voids volume;
- The type of granulometric curve of the aggregates.

As previously reported, previous research has indicated that macrotexture is affected by the maximum nominal aggregate size, which is defined as the smallest sieve through which 100% of the aggregate sample will pass.

The types of aggregates used in this study were limestone (sedimentary rock) and gravel. These types were selected because they are commonly used and are both abundant in Wisconsin. The percentage of air voids in an asphalt mixture can significantly affect the performance of asphalt pavement. Voids in asphalt mixtures (at optimum binder content) can be reduced from about eight percent at

the beginning of a road's life to about three percent after a significant traffic load. The voids used in this study were between four and eight percent for hot mix asphalt mixtures, and for porous asphalt mixtures, the voids were between 15 and 20%.

A significant aspect in the roughness of a road pavement during the service period is the polishing of the aggregates. The related issue to consider is the gradual (microscopic) wear of homogeneous aggregates to determine the relevant physical properties of these minerals in the wear process. Wear is measured as a weight loss of the material.

The importance of the types of aggregates used in the mixtures of rough asphalt concrete also derives from the degree of wear. Microscopic study of worn surfaces revealed two phenomena: scratches and disintegration. Fast-wearing minerals tend to show both types of damage, while slow-wearing minerals do not show scratches, only a small amount of disintegration. Rapid wear occurs when the abrasive was harder than the mineral. Wear is proportional to the load and inversely proportional to the hardness. Slow wear of minerals less hard than abrasive was independent of load. Disaggregation is related to energy concepts, while scratching was related to hardness. However, the hardness of the aggregates proved to be the most important parameter in the rapid wear of homogeneous minerals.

The predominant variable in tire-road surface friction under wet road conditions is the texture of the road surface itself. Skid resistance depends on a surface that ensures the penetration of the water film and drainage channels. One of the factors that can change these characteristics is the smoothing and rounding of the aggregates in the asphalt mixture exposed by the abrasives found on the road. This process is caused by the removal of particles or wear on a microscopic scale and is commonly referred to as sanding. The amount of wear over a period of time can have a direct effect on the skid resistance of road pavement. The cause for concern here is the gradual (microscopic) wear of the homogeneous aggregates contained in the bituminous mixture.

4. Asphalt mixtures in Romania

Asphalt pavement mixtures are construction materials made from mixes obtained on a dosage judiciously determined basis, from natural or artificial aggregates and filler, agglomerated with bitumen through an appropriate technology. They have multiple usage, being mainly used for construction of flexible road pavements and base layers. The most used asphalt mixes aggregates are: stone of all kinds, natural and crushed sands, ballast and crushed ballast and gravel, artificial aggregates such as sorted blast furnace slag, granulite, crushed pile slag, etc. Under certain conditions it can be used quarry waste, industrial by-products, etc. The choice of natural aggregates must be made with discernment, knowing that under certain conditions a wide range of local materials processed and treated can be used, which leads to asphalt mixes with satisfactory technical characteristics, which are cost efficient.

The conditions that natural aggregates must meet in order to be used in road pavements are well defined and refer to the size and shape of the aggregate, the nature of the road support, granularity, etc. They must be particularly clean, have good adhesion to the bitumen used, have adequate mechanical strength and be resistant to wear. The most frequently used filler with the best results is obtained by grinding limestone. The bitumen used in road pavements has a decisive importance in their behavior, its type being chosen depending on the asphalt mix we want to prepare, more precisely the physical-mechanical characteristics considered for the mixture. One can use pure bitumen, modified bitumen, additive bitumen, bitumen derivatives (bituminous emulsion, cut bitumen). Regarding the consistency of the bitumen used, it varies in a wide range depending on the type of asphalt mix. If the bitumen currently used is type D 80/120, there is a general tendency to use

harder bitumen (D 50/80), which gives asphalt mixes a higher stability in conditions of heavy traffic and high temperatures.

Natural aggregates used in asphalt mixes must have a number of characteristics, in particular the following: to be clean; to show as little wear as possible under the traffic; to be homogeneous in terms of mineralogical composition; to come from rocks of a basic or neutral nature, which allow a good adhesiveness to be achieved; if, however, acid rock aggregates are used, it is absolutely necessary either to add surfactants to the bitumen or to treat the aggregates with these substances or with lime; to have high compressive strength, so they don't shatter under traffic and weather effect; the shape of the aggregates should be polyhedral.

To increase the compactness, filler is added, which reduces the volume of voids in the mix, but increases the specific surface area of the natural aggregate. The filler increases the plasticity of the bitumen and favors the adhesion to the natural aggregate. At the same time, it increases the internal friction of the bitumen and the cohesion and thereby improves the behavior of the asphalt mix. Bitumen mixed with filler hardly changes its chemical composition. The filler prevents the bitumen from aging by acting so that the bitumen retains its binder properties for a long time. The dosage judiciously dosed in relation to the other components increases the compactness and the specific surface of the natural aggregate, thus ensuring, together with the bitumen, the mechanical resistance and the stability at high temperatures of the asphalt mixes. However, the excess filler is harmful, as the mechanical strength and stability at high temperatures decrease, and lumps form in the asphalt mix, reducing its workability. Overdose bituminous coating has surface irregularities and is less resistant to water. In order to obtain a maximum resistance of the asphalt mix, it is necessary that all the natural aggregate be covered with a bituminous film as thin as possible. The higher the thickness of the bitumen film, the lower the resistance to shear and plastic deformation. Obtaining such a fine bitumen film is only possible by fillerization. Laboratory studies performed on asphalt concretes, following the relationships filler-volume of voids, filler-cohesion of the asphalt mix and the resistance to plastic deformations under the action of the track simulator led to the following conclusions:

- the ratio between bitumen and filler is an important factor in terms of stability. The filler modifies the properties of the binder, leading to a better viscosity. This fact justifies the theory that the filler acts not only on reducing the volume of voids, but with the help of its very fine particles, it modifies the properties of the bitumen.
- the addition of asbestos fibers, as a filler, in proportion 1... 3% has a favorable effect on the cohesion of the asphalt mixture and its good behavior under traffic.

The term "bituminous materials" generally includes all materials consisting of aggregates coated with either bitumen or tar, the latter term being a binder used predominantly before the bitumen era. Bituminous materials are used almost exclusively in road construction, although bitumen is also used successfully for industrial applications and other forms of construction, such as roofing elements, paints, special waterproofing coatings, etc. Today, a wide variety of bituminous materials are used in construction, each with its own distinctive features. The selection of appropriate materials for each application is based on technical, economic and environmental criteria [10].

The United Nations Statistics Division estimates that world bitumen production in 2018 was about 119 million tons [10]. Currently, bitumen has over 250 known applications, the majority of which are still used in road construction and civil engineering, for roof waterproofing. It is estimated that 85% of the total bitumen produced is used in transport infrastructure, as a binder in various bituminous mixtures. About 10% of the bitumen is used for roofs (eg shingles, hot-applied built roofs, cold-rolled roofs, etc.) and (c) the remaining part (about 5% of the total) is used for a variety of applications (coating for water pipes, bitumen paints, waterproofing

and sealing materials, etc.); this sector is generally called other applications "[11-13]. According to Eurobitume [13], "approximately 93% of all bitumen supplied in Europe in 2017 went to the road sector, while the remaining 7% went to industrial and other applications". Bitumen is mainly used in bituminous mixtures, which, according to ISO 15642 [14], is defined as a "homogeneous conglomeration of building materials consisting of sized mineral aggregates, possibly additives and fillers, coated collectively and uniformly with binder".

5. Case studies. Roughness measurement on national roads in Romania

One of the necessary conditions for traffic safety is to ensure a proper roughness, by achieving a good grip between the tire and the pavement surface in order to increase its anti-skid quality. Road roughness is characterized by the value of the SRT or MTD indicator. The roughness of rigid road pavements can be determined only by the MTD method, but for bituminous pavements the two methods can be used in parallel, adopting the most unfavorable grade.

The MTD method consists in spreading on the analyzed surface a volume of 25 cm^3 of fine sand in the form of a circular spot. The sand will fill the road pavement voids to the level of roughness. MTD is determined by relating the volume of sand to the surface of the stain.

SRT - Skid Resistance Test (Fig 1) allows the assessment of road roughness by measuring the skid resistance between the pendulum of the SRT device and the road pavement surface.

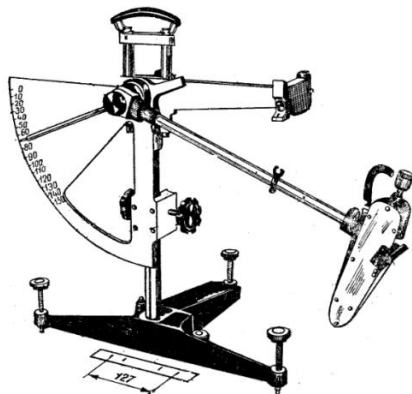


Fig. 1 SRT device - Skid Resistance Test [15]

Experimental studies on the roughness of road pavements by determining the microtexture, as well as macrotexture have been conducted in Romania, in order to establish the correlation between these two characteristics which have a significant impact on the skid resistance of road pavements. Therefore, through the Road Laboratory belonging to the Iasi Regional Directorate, tests were carried out to establish the exact value of the skidding characteristics. The tests are part of the admissibility conditions that must be met when constructing / rehabilitating road pavement sections, a lower value means that the road sector does not meet the minimum skidding resistance.

Therefore, studies were carried out on establishing the roughness on the national roads. As follows is presented only the results obtained on the roads DN 2 km 212 + 000 and DN 15 km 290 + 870. The tests performed are in accordance with the provisions of the regulations SR EN 13036-1: 2010 and PTE D-36 [16], for macrotexture, respectively SR EN 13036-4: 2012 and PTE D-37 [17] for adhesion by the SRT pendulum method.

Macrotexture measurement

These measurements were carried out during the execution of the pavement maintenance works, in order to establish the fulfillment of the roughness criteria.

DN 2 km 212+000 ÷ 212+040

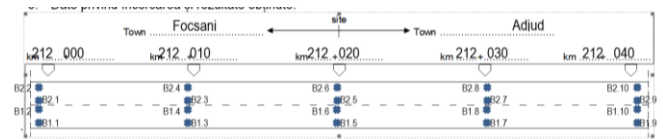


Fig. 2 In-situ placement of positions under investigation

Table 1: Data and calculations regarding the determination of the depth of the macrotexture of the pavement surface by the volumetric technique MTD - right lane DN 2 km 212 + 000 ÷ 212 + 040

Indicative test surface, code / no.	V, mm ³	Diameter mm				Di, mm	MTDi, mm	Obs.
		D1	D2	D3	D4			
B1.1	25000	175	164	164	169	168	1.13	1m from shoulder
B1.2		170	168	165	160	166	1.16	0.5m from axis
B1.3		162	162	161	169	164	1.19	1m from shoulder
B1.4		158	155	159	152	156	1.31	0.5m from axis
B1.5		151	152	153	152	152	1.38	1m from shoulder.
B1.6		150	158	159	160	157	1.30	0.5m from axis
B1.7		179	178	169	174	175	1.04	1m from shoulder
B1.8		155	157	158	160	158	1.28	0.5m from axis
B1.9		155	152	160	156	156	1.31	1m from shoulder
B1.10		155	156	160	160	158	1.28	0.5m from axis
							1.24	

Table 2: Data and calculations regarding the determination of the depth of the macrotexture of the pavement surface by the volumetric technique MTD - left lane DN 2 km 212 + 000 ÷ 212 + 040

Indicative test surface, code / no.	V, mm ³	Diameter, mm				Di, mm	MTDi, mm	Obs.
		D1	D2	D3	D4			
B2.1	25000	152	155	158	160	156	1.30	0.5m from axis
B2.2		171	167	172	166	169	1.12	1m from shoulder
B2.3		154	150	160	157	155	1.32	0.5m from axis
B2.4		170	170	160	157	164	1.18	1m from shoulder
B2.5		152	160	160	157	157	1.29	0.5m from axis
B2.6		153	148	150	146	149	1.43	1m from shoulder
B2.7		160	162	165	168	164	1.19	0.5m from axis
B2.8		160	155	160	163	160	1.25	1m from shoulder
B2.9		144	153	147	152	149	1.43	0.5m from axis
B2.10		175	165	180	170	173	1.07	1m from shoulder
							1.26	

Given that the national road DN 2, km 212 + 000 in terms of traffic is a road of technical class II, according to the roughness criteria established by AND 605 [18], the pavement meets the minimum conditions regarding MTD, the average values established on the road being greater than 1.2. Based on this consideration, the pavement has an appropriate roughness and the condition of skidding resistance is met.

DN 15 km 290+850 ÷ 290+890

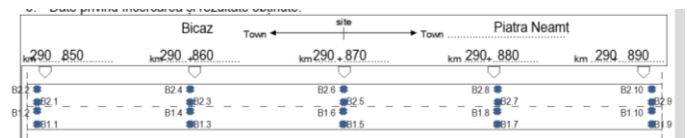


Fig. 3 In-situ placement of positions under investigation

Table 3: Data and calculations regarding the determination of the depth of the macrotexture of the surface pavement by the volumetric technique MTD - right lane DN 15 km 290 + 850 ÷ 290 + 890

Indicative test surface, code / no.	V, mm ³	Diameter, mm				Di, mm	MTDi, mm	Obs.
		D1	D2	D3	D4			
B1.1	25000	382	348	365	387	371	0.23	
B1.2		351	407	362	379	375	0.23	
B1.3		359	348	334	362	351	0.26	
B1.4		359	362	373	337	358	0.25	

B1.5		328	302	334	318	321	0.31	
B1.6		321	317	309	334	320	0.31	
B1.7		318	334	317	327	324	0.30	
B1.8		301	294	295	318	302	0.35	
B1.9		348	329	326	330	333	0.29	
B1.10		274	278	272	294	280	0.41	
							0.29	

Table 4: Data and calculations regarding the determination of the depth of the macrotexture of the surface pavement by the volumetric technique MTD - left lane DN 15 km 290 + 850 ÷ 290 + 890

Indicative test surface, code / no.	V, mm ³	Diameter, mm				D _i , mm	MTD _i , mm	Obs.
		D ₁	D ₂	D ₃	D ₄			
B2.1	25000	332	349	347	342	343	0.27	
B2.2		253	238	255	245	248	0.52	
B2.3		348	331	345	350	344	0.27	
B2.4		263	265	265	254	262	0.46	
B2.5		373	358	303	361	349	0.26	
B2.6		262	258	257	265	261	0.47	
B2.7		289	262	275	274	275	0.42	
B2.8		295	283	297	290	291	0.38	
B2.9		255	254	265	245	255	0.49	
B2.10		301	295	303	296	299	0.36	
							0.39	

Considering that the national road DN 15 km 290 + 890 from the traffic point of view is a road of technical class II, according to the roughness criteria established by AND 605 [18], the pavement does not meet the minimum conditions regarding MTD, the average values established on the pavement being less than 1.2. Based on this consideration, the road does not have a proper roughness and the condition of skid resistance is not met, and applying additional measures are needed to increase the roughness, such as the execution of a roughness treatment.

Measurement of pavement surface adhesion by pendulum test method

DN 2 km 212+000 ÷ 212+040

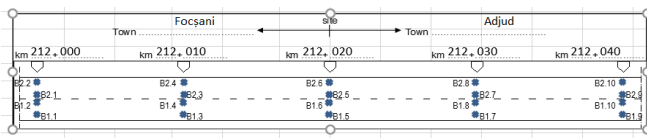


Fig 4 In-situ placement of positions under investigation

Table 5: SRT values determined on site DN 2 km 212 + 000 ÷ 212 + 040 left lane

Surface identification, code / no.	SRT roughness obtained, PTV units					SRT average value, PTV units	Temp. Correction, PTV units	SRT value, PTV units	Obs.
	1	2	3	4	5				
B2.1	75	75	75	75	75	75	-4	71	0.5m from axis
B2.2	74	74	74	73	73	74	-4	70	1m from shoulder
B2.3	79	79	79	79	79	79	-4	75	0.5m from axis
B2.4	72	72	72	72	72	72	-3	69	1m from shoulder
B2.5	80	80	80	80	79	80	-2	78	0.5m from axis
B2.6	73	73	73	73	72	73	-2	71	1m from shoulder
B2.7	73	73	73	72	72	73	-4	69	0.5m from axis
B2.8	77	77	77	77	78	77	-3	74	1m from shoulder
B2.9	72	72	72	71	71	72	-2	70	0.5m from axis
B2.10	73	73	73	73	73	73	-3	70	1m from shoulder
									72

DN 2 km 212+000 ÷ 212+040 right lane

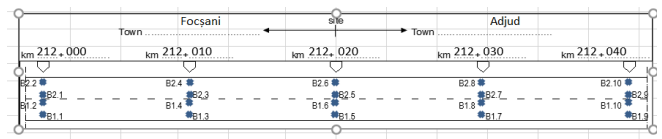


Fig. 5 In-situ placement of positions under investigation

Table 6: SRT values determined on site DN 2 km 212+000 ÷ 212+040 right lane

Surface identification, code / no.	SRT roughness obtained, PTV units					SRT average value, PTV units	Temp. Correction, PTV units	SRT value, PTV units	Obs.
	1	2	3	4	5				
B1.1	70	71	71	71	70	71	-1	70	1m from shoulder
B1.2	72	72	71	72	72	72	-2	70	0.5m from axis
B1.3	76	76	76	76	76	76	-2	74	1m from shoulder
B1.4	77	77	77	78	77	77	-3	74	0.5m from axis
B1.5	73	73	73	72	72	73	-4	69	1m from shoulder
B1.6	74	74	74	75	74	74	-4	70	0.5m from axis
B1.7	76	76	76	75	75	76	-4	72	1m from shoulder
B1.8	77	77	77	78	77	77	-4	73	0.5m from axis
B1.9	78	78	78	77	77	78	-3	75	1m from shoulder
B1.10	78	78	78	77	77	78	-3	75	0.5m from axis
									72

Given that the national road DN 2, km 212 + 000 is a road of technical class II, according to the roughness criteria established by AND 605 [18], the pavement does not meet the minimum conditions regarding the minimum admissible SRT value (the pavement must present it, the average of the established values on the sector being larger than 80). Based on this consideration, the road does not have a proper roughness and the condition of skid resistance is not met, and it is necessary to apply methods to increase the roughness, such as the execution of roughness treatments. Although the MTD value came out properly, corroborated with the SRT value, it is considered that the road does not meet the minimum roughness condition.

Measurement of tread adhesion by test method with pendulum DN 15 km 290 + 850 ÷ 290 + 890 right lane

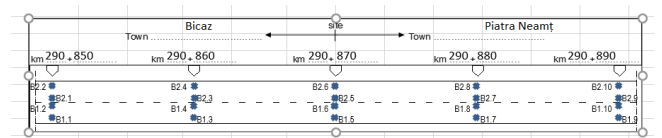


Fig. 6 In-situ placement of positions under investigation

Table 7: SRT values determined on site DN 15 km 290 + 850 ÷ 290 + 890 right lane

Surface identification, code / no.	SRT roughness obtained, PTV units					SRT average value, PTV units	Temp. Correction, PTV units	SRT value, PTV units	Obs.
	1	2	3	4	5				
B1.1	57	56	56	56	55	56	-1	55	1m from shoulder
B1.2	59	59	59	59	59	59	-2	57	0.5m from axis
B1.3	58	57	57	56	56	57	-2	55	1m from shoulder
B1.4	58	58	58	58	58	58	-2	56	0.5m from axis
B1.5	58	58	58	57	57	58	-2	56	1m from shoulder
B1.6	56	55	55	55	54	55	-2	53	0.5m from axis
B1.7	57	57	56	56	56	56	-2	54	1m from shoulder
B1.8	56	56	55	55	56	56	-2	54	0.5m from axis
B1.9	58	59	60	58	58	59	-2	57	1m from shoulder
B1.10	56	56	55	56	56	56	-2	54	0.5m from axis
									55

Measurement of pavement surface adhesion by the test method with pendulum DN 15 km 290 + 850 ÷ 290 + 890 left lane

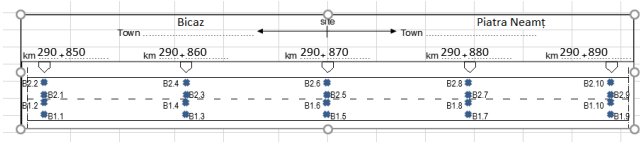


Fig. 7 – In-situ placement of positions under investigation

Table 8: SRT values determined on site DN 15 km 290 + 850 ÷ 290 + 890 left lane

Surface identification, code / no.	SRT roughness obtained, PTV units					SRT average value, PTV units	Temp. Correction, PTV units	SRT value, PTV units	Obs.
	1	2	3	4	5				
B2.1	56	56	56	56	55	56	-2	54	0.5m from axis
B2.2	63	62	62	61	62	62	-1	61	1m from shoulder
B2.3	55	55	54	54	54	54	-2	52	0.5m from axis
B2.4	63	63	63	64	63	63	-2	61	1m from shoulder
B2.5	58	58	58	59	58	58	-2	56	0.5m from axis
B2.6	53	53	53	53	52	53	-1	52	1m from shoulder
B2.7	53	53	52	53	53	53	-2	51	0.5m from axis
B2.8	66	66	66	66	66	66	-2	64	1m from shoulder
B2.9	56	56	57	57	57	57	-1	56	0.5m from axis
B2.10	63	63	63	63	63	63	0	63	1m from shoulder
								56	

Given that the national road DN 15, km 290 + 870 is a road of technical class II, according to the roughness criteria established by AND 605 [18], the pavement does not meet the minimum conditions regarding the minimum SRT value that the pavement must present, the average of the established values on the sector being less than 80. Based on this consideration, the road does not have a proper roughness and the condition of resistance to skidding is not met, requiring the application of adequate methods to increase the roughness, such as the execution of roughness treatments.

6. References

1. Highway Research Board, Special Report 101. Control of Pavement Slipperiness. Asphalt Pavement Cracking, Proceedings of the Western Summer Meeting, Cosponsored by the Colorado Department Of Highways, Held August 12-13, 1968, Denver, Colorado, (1969)
2. D. Noyce, B. Hussain, J. Yambo, J. Chapman, A. Bill, Incorporating Road Safety into Pavement Management: Maximizing Surface Friction for Road Safety Improvements, Midwest Regional University Transportation Center, College of Engineering, Department of Civil and Environmental Engineering, University of Wisconsin, Madison, (2007)
3. P. Cairney, Skid Resistance and Crashes – A Review of the Literature. Research Report No. 311, ARRB Transport Research Ltd, Vermont South Victoria, Australia, (1997).
4. P.W. Jayawickrama, R. Prasanna, S.P. Senadheera, Survey of State Practices to Control Skid Resistance on Hot-Mix Asphalt Concrete Pavements, In Transportation Research Record: Journal of the Transportation Research Board, No. 1536, TRB, National Research Council, Washington, D.C., pp. 52-58, (1996).
5. V. Galambos, B. Hegmon, Rice, Kopac, Brinkman. Pavement Texture and Available Skid Resistance, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., (1977).
6. F.L. Roberts, P.S. Kandhal, E.R Brown, D-Y. Lee, and T.W. Kennedy. Hot Mix Asphalt Materials, Mixture Design, and Construction. 2nd Edition, NAPA Research and Education Foundation, Lanham, Maryland, (1996).
7. ASTM E965-15 Standard Test Method for Measuring Pavement Macrottexture Depth Using a Volumetric Technique (2019)

8. A. Surchamp, Collecteur par enrobes Drainants sur Peripherique Parisien. Route Axualites, No. 4, (1995).
9. Ministerie van Verkeer en Waterstaat, Structuurschema Verkeer. Vervoer, (1991).
10. B. Revuelta M. Bituminous Materials. In: Construction Materials. Springer Textbooks in Earth Sciences, Geography and Environment. Springer, Cham. https://doi.org/10.1007/978-3-030-65207-4_14, Print ISBN 978-3-030-65206-7, online ISBN 978-3-030-65207-4 (2021)
11. Asphalt Institute Inc. and European Bitumen Association–Eurobitume, Information Series No. 230, 60 p, (2021)
12. Asphalt Institute. www.asphaltinstitute.org
13. Eurobitume. www.eurobitume.eu
14. ISO 15642, Road construction and maintenance equipment — Asphalt mixing plants — Terminology and commercial specifications (2003)
15. STAS 8849, Lucrari de drumuri. Rugozitatea suprafetelor de rulare. Metode de masurare/ Road works. Pavement surface roughness. Measurement methods (1983)
16. R EN 13036-1, Caracteristici ale suprafetei drumurilor si aeroporturilor. Metode de incercare. Partea 1: Masurarea adancimii macrotexturii suprafetei imbracamintei, prin tehnica volumetrica a petei/ Road and airport surface pavement characteristics. Test methods. Part 1: Measurement of the macrottexture depth of the pavement surface, using the volumetric stain technique (2010)
17. SR EN 13036-4, Caracteristici ale suprafetelor drumurilor si pistelor aeroportuare. Metode de incercare. Partea 4: Metode de masurare a aderentei unei suprafete: incercarea cu pendul/ Road and airport surface pavement characteristics. Test methods. Part 4: Methods for measuring surface adhesion: pendulum testing (2012)
18. AND 605, Normativ mixturi asfaltice executate la cald. Conditii tehnice privind proiectarea, prepararea si punerea in opera/Hot asphalt mixes. Technical conditions for design, preparation and execution (2014)

Study of the effects on engine fuel consumption generated by turbocharger performance

Dimitar Popov

¹ Nikola Vaptsarov Naval Academy, Varna, Bulgaria
d.popov@nvna.eu

Abstract: Damage to the turbocharger of the 8400kW diesel engine, which had operated about 66 640 running hours, has caused off hire of the vessel for 10 days and the turbocharger repair had cost more than half a million euros. The study performed on this work consists of evaluating the consequences of the low turbocharger performance on the fuel oil consumption and the reasons for this. Specific data were collected and analysed in order to create an appropriate mathematical model between the studied parameters. Measurements and data collected were performed a month before turbocharger damage and after the TC overhaul (with new cartridge). As results can be concluded that losses in turbocharger performance is very important for the efficient operation of the main engine, they must be monitored and analysed.

Keywords: TURBOCHARGER, MARINE DIESEL ENGINE, PERFORMANCE, FUEL CONSUMPTION, REGRESSION ANALYSIS.

1. Introduction

Turbochargers (TC) are used with internal combustion engines to increase power output, reduce fuel consumption, and reduce emissions. As one of the key systems of the marine power plant diesel engine, the turbocharger directly affects whether the diesel engine can continuously and stably provide the power required for the ship. At present, the fault diagnosis of the marine turbocharger has not been paid enough attention yet and in most cases, the method of 'ex post diagnosis' is still adopted. The current turbocharger fault diagnosis method mostly adopts single-machine and offline mode and has certain hysteresis. Various performance parameters observed during the operation of the equipment are processed and analyzed to determine whether a damage has occurred, the type of fault and its cause. It is necessary to adopt a new method based on the existing fault diagnosis theory and technology, to obtain a diagnostic model that can solve practical problems [4, 5].

The aim of this research is to provide a review of influence of turbocharger technical condition on engine fuel consumption and the reasons for turbocharger low performance. Our target is by collected data to find appropriate mathematical methods to obtain qualitative relationships between the engine fuel consumption and turbocharger revolutions.

The objects of research was a four-stroke medium speed marine engines MAK 9M43C type with its ABB turbocharger TPL76-C33 type located on aft end of the engine (fig. 1) [2].

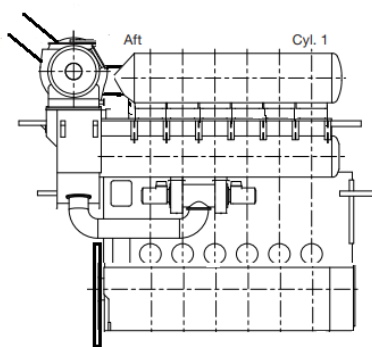
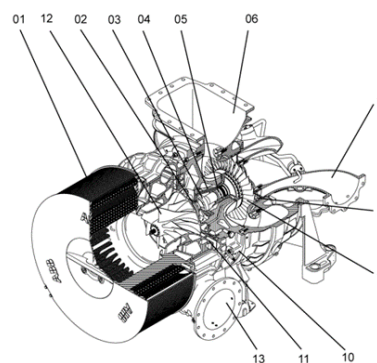


Fig. 1: One turbocharger located on aft end.

The turbocharger components are shown in fig. 2 as bellow [12, 13]:

- 1.Filter silencer
- 2.Radial plain bearing
- 3.Thrust bearing
- 4.Bearing bush
- 5.Radial plain bearing
- 6.Gas outlet casing



- 7.Gas inlet casing
- 8.Nozzle ring
- 9.Turbine wheel
- 10.Bearing casing
- 11.Diffuser
- 12.Compressor wheel
- 13.Compressor casing

During a sea passage of the vessel the main engine was operating at load about 50 % of nominal power. The TC temperature inlet (T_{in}) was 752K and TC outlet temperature (T_{out}) was 691K. The speed on the turbocharge was 148 s^{-1} . The data was still within the limits of normal operation. On 02nd February 2021 at 02:00 LT the duty engineer called the bridge to reduce the load of the engine as there was an unusual noise from the turbocharger side. After primary checking of the main engine had observed high exhaust gas temperatures and metal particles in the lube oil filter. Lube oil filter high differential pressure alarm had found active.

The subjected turbocharger was thoroughly inspected and investigated by the chief engineer on board of the vessel. The turbocharger / Cartridge was carefully disassembled for inspection and assessment of the components, findings have been documented by means of photographs. The components have been visually assessed. The investigation has been focused on possible causes and contributing factors. The objective of the investigation is to determine how the subjected issue had happen.

Considering the information available following possible failure causes could have led to the failure of cartridge smooth rotation and the excessive axial movement of compressor wheel supports increase of clearances in radial and axial bearing beyond the limits. This further validates that the bearings and shaft have worn beyond usable limits. The rubbing of the compressor wheel (fig.3) with wall insert may be the consequential damage [3, 10, 11].

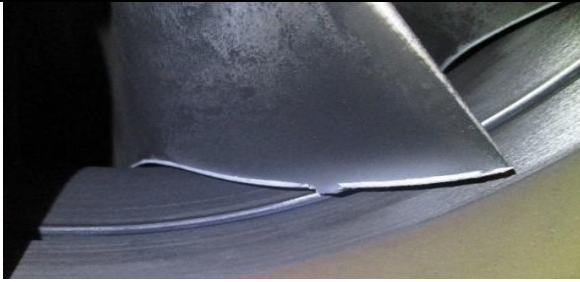


Fig. 3: Rubbing of the compressor wheel.



Fig. 4: Presence of unburnt oil along with carbon deposits.

Inspection of other components on board (refer figure 4) relates the fact that there was presence of unburnt oil along with carbon deposits. This could likely be the reason of unbalance in the shaft which might have led to rubbing of compressor wheel and ultimately leading to failure of other components.

From another point of view there is a possibility of lube oil starvation which would have led to the damages to the bearings and shaft ultimately resulting in failure of other components.

With regard to contamination (fig. 5), water has penetrated in the gas outlet housing, which has caused contamination by mixing with unburnt oil and carbon [1], leading to unbalance in the shaft and further causing failure of other components.



Fig. 5: Contamination by mixing with unburnt oil, carbon, water.

With available information, failure of cartridge group could likely be from the 3 probable reasons: Presence of unburnt oil, Lube oil Starvation, Presence of water [14, 15].

2. Statistical analysis

It is very important to note that due to a good combination of circumstances, the presented data were collected a month before the accident as well as for a month after the repair of the turbocharger. Therefore, we can certainly exclude the influence of the technical condition of the engine (fuel valves, fuel pumps, piston-cylinder liner group, exhaust valves, etc.) [6, 7, 8, 9] on operation condition

of the turbocharger. Moreover, the used data had been collected in almost the same load condition of the vessel.

The research technology covers two stages.

The first step is to gather appropriate information parameters before the turbocharger is damaged and the same information parameters after repairing the turbocharger.

In statistical modelling, regression analysis is a set of statistical processes for estimating the relationships between a dependent variable (often called the 'outcome') and one or more independent variables (often called 'predictors'). In our case a dependent variable "x" is the turbocharger revolutions (n, s^{-1}) from one side and from another an independent variable "y" – the engine fuel oil consumption ($Bs, kg/s$). Once a regression model has been constructed, we can confirm the goodness of fit of the model and the statistical significance of the estimated parameters. Commonly used checks of goodness of fit include the R-squared. The Pearson correlation coefficient (R), is a measure of the strength and direction of the linear relationship between x and y. This is the best-known and most commonly used type of correlation coefficient.

The collected data and the obtained mathematical model provide a basis for future analyzes and checks on the condition of the turbocharger, as well as for continuous monitoring. Logically, we can assume that an error in the data used in the range of 4-5 % is permissible within the measuring instruments, as well as the operator. Following the logical reasoning, we can conclude that the error above the mentioned 4-5 % is not due to the means of instrument error, but due to the causal relationship between the dependent variable x and the independent variable y. The larger error, the stronger relationship between x and y. The main advantage of regression analysis is that the contribution of each parameter can be quickly quantified.

The used data was collected one month before the T/C failure and the same data was collected after the T/C overhaul are given in the following table 2 and table 3.

Table 2. Before damage

TCrev., [1/s]	Bs, [kg/s]
x1	y1
158,33	0,1383
158,33	0,1451
158,33	0,1473
163,33	0,1594
165	0,1722
191,67	0,2106
170	0,1684
175	0,1863
186,67	0,1865
186,67	0,184
203,33	0,2051
213,33	0,1979
215	0,2273
216,67	0,206
230	0,256
246,67	0,2667
248,33	0,3063
263,33	0,3215

Table 3. T/C overhauled.

TCrev., [1/s]	Bs, [kg/s]
x2	y2
183,33	0,1919
213,33	0,2175
218,33	0,2434
230	0,2675
231,67	0,259
231,67	0,2528
241,67	0,2553
246,67	0,2754
248,33	0,2718
250	0,2628
250	0,2659
250	0,2688
251,67	0,2865
258,33	0,2821

The second step was to find mathematical models proving the causal relationship between the factor x_i and the objective function y_i . In order to run a statistical analysis a number of significant parameters, responding to equation (1), must be identified [16].

$$y = f(x_i) + e \quad (1)$$

The regression analysis was run by excel app using the data in table 2 and table 3. The regression curve was drawn by a scatter plot and line equations and the R^2 value was displayed at figure 7.

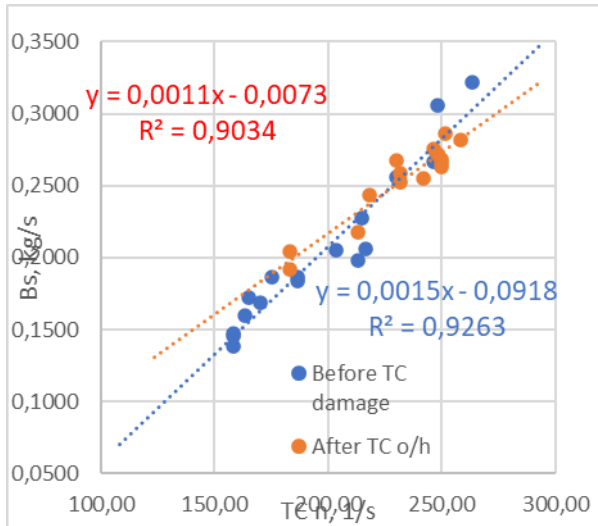


Fig. 7. Influence of fuel consumption Bs to the TC revolutions n.

Before TC damage we found a linear relationship between x and y as follows:

$$y1 = 0.0015 \cdot x - 0.0918 \quad (2)$$

In case with repaired TC the linear relationship between x and y was found as follows:

$$y2 = 0.0011 \cdot x - 0.0073 \quad (3)$$

According to the represented interest of TC revolutions in the range from 180 s^{-1} to 264 s^{-1} , using the dependences obtained from the regression analysis, we can record the obtained and predicted values for $y1$ and $y2$ by applying values for x (n). To determine the error in percentages (y_e) between $y1$ and $y2$, we need to calculate the difference between $y1$ and $y2$ (Δy) and then the error y_e , % by below equations (4) and (5) :

$$\Delta y = y1 - y2 \quad (4)$$

$$y_e = (\Delta y / y1) \cdot 100, \% \quad (5)$$

The results obtained from the used formulas are shown in tabular form in table 4.

Fig. 8 represents polynomial dependence of the error in percentages to the TC revolution between a turbocharger with new cartridge and a turbocharger for forthcoming repairs. We have note that TPL 76-C33 max. revolutions are 342 s^{-1} . So, in the researched interval of rotation $180 - 264 \text{ s}^{-1}$ the error is in range of 6.55 % to -7.45 %.

Table 4: Predicted value $y1$, $y2$ and y_e .

n, 1/S	Bs1, kg/s	Bs2, kg/s		
x	y1	y2	Δy	y_e , %
180	0,191	0,178	0,013	6,55
187	0,198	0,189	0,01	4,89
194	0,206	0,199	0,007	3,35
201	0,214	0,21	0,004	1,92
208	0,222	0,22	0,001	0,59
215	0,229	0,231	-0,002	-0,65
222	0,237	0,241	-0,004	-1,82
229	0,245	0,252	-0,007	-2,9
236	0,252	0,262	-0,01	-3,92
243	0,26	0,273	-0,013	-4,88
250	0,268	0,283	-0,016	-5,79
257	0,275	0,294	-0,018	-6,64
264	0,283	0,304	-0,021	-7,45

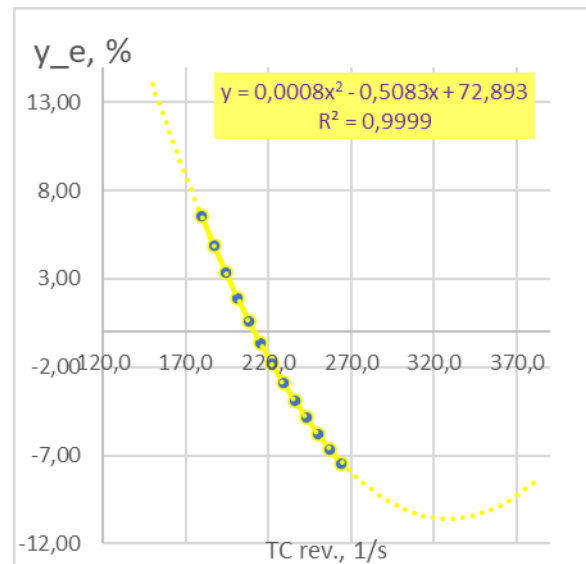


Fig.8: Polynomial dependence of the error.

3. Conclusion

- 3.1 According to the information and data collected, the damage to the cartridge group can be due to 3 possible reasons: - Presence of unburned oil, Lube oil starvation, Presence of water. Therefore, in case of suspicion of malfunction or deviation from the normal condition, the responsible engineers must carry out the appropriate checks and measurements prescribed by the manufacturer, regardless of the working hours provided for in the maintenance schedule.
- 3.2 The present result shows that there is no relationship between the change in turbine speed (due to poor technical condition) and the fuel oil consumption of the engine. The calculated error y_e is in the range $\pm 7\%$ only at low and high loads of the main engine. In the most used engine modes (30% - 80%) the error is less than 4%, which confirms the conclusion.

4. References

1. Bakalov I., Constructive solutions to reduce the NO_x and SO_x in the marine boiler burners. Varna, 2016, ISSN: 1310-3946
2. Caterpillar Motoren GmbH & Co. KG, Engine operating instructions Type M43C, 17.05.2006
3. Cimac, Turbocharging efficiencies - definitions and guidelines for measurement and calculation, www.cimac.com, May 2007
4. Cui X., Yang C., Serrano J., Shi M., A performance degradation evaluation method for a turbocharger in a diesel engine, , rsos.royalsocietypublishing.org R. Soc. open sci. 5: 181093
5. Habib A., On-Engine Turbocharger Performance Considering Heat Transfer, TRITA – MMK 2012:08, ISSN 1400-1179, ISRN/KTH/MMK/R-12/08-SE, ISBN 978-91-7501-332-9, 22nd of May 2012.
6. Hristov, D., Examination of the influence of the air cooler contamination and the piston rings wear on the marine diesel engines BSFOC, NO_x and SO_x, Scientific proceedings XIV international congress "Machines. Technologies. Materials." 2017, ISSN 2535-0021
7. Hristov D., Ivanov, I. Study of the impact of technical condition of the turbocharger unit on nitrogen oxides emissions of engine running on natural gas with pre-chamber ignition and lean fuel-air mixture, Nikola Vaptsarov Naval Academy, Doctoral scientific conference 18-19 Nov, Varna p.30-35 ISBN 978-619-7428-45-2 (print) ISBN 978-619-7428-44-5 (online), 2019
8. Hristov, D., Ivanov, I., Hristov, H. Study of the impact of air cooler contamination and piston rings wear on engine emissions, Mechanics of the machines, 2018, v. 24, № 2. ISSN 0861-9727
9. Hristov D., Ivanov I., Bakalov, I. Turbocharger Technical Condition Influence on the Carbon Dioxide Emissions on Natural Gas Fueled Engine, First International Marine Engineering Conference, 21-23 November 2018 at the Engineering Faculty Nikola Vaptsarov Naval Academy. Varna: NVNA, 2018, pp. 187-191. ISBN 978-619-7428-31-5.
10. Ibrahim M, Dimitri A.S., Bayoumi H.N., El-Shafei A., Stable turbocharger bearings, 12th International Conference on Vibrations in Rotating Machinery Institution of Mechanical Engineers, ISBN 978-0-367-67742-8
11. Iosifov I., Hristov D., Problems with the low temperature corrosion on the marine turbochargers XXIV international scientific-technical conference "trans & motauto '16" 2016 ISSN 1310-3946
12. Jeonha-Dong, Dong-Ku, Instructions Hyundai-MAN B&W diesel engines operation, Hyundai Heavy Industries Co., Ltd., Edition 0005, Ulsan, Korea
13. Kusztelan A., Yao Y.F., Marchant D.R., Wang Y., A Review of Novel Turbocharger Concepts for Enhancements in Energy Efficiency, Int. J. of Thermal & Environmental Engineering, Volume 2, No. 2 (2011) 75-82
14. Romagnoli A. and Martinez-Botas R., Heat transfer analysis in a turbocharger turbine: an experimental and computational evaluation, Department of Mechanical Engineering Imperial College London, UK, 2012
15. Serrano, J., Olmeda P., Arnau F., Reyes-Belmonte M., Importance of Heat Transfer Phenomena in Small Turbochargers for Passenger Car Applications, Universitat Politècnica de València, saeeng.saejournals.org, 2013-01-0576
16. Бакалов И., Р. Бакалова. Използване на алтернативни горива в корабните дизелови двигатели, икономически фактор. Шумен, "Маттех 2014", ISSN: 1314-3921