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# ROBUST TRAJECTORY TRACKING CONTROL FOR AUTONOMOUS VEHICLE SUBJECT TO VELOCITY-VARYING AND UNCERTAIN LATERAL DISTURBANCE

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## *Abstract:*

*Autonomous vehicles are the most advanced intelligent vehicles and will play an important role in reducing traffic accidents, saving energy and reducing emission. Motion control for trajectory tracking is one of the core issues in the field of autonomous vehicle research. According to the characteristics of strong nonlinearity, uncertainty and changing longitudinal velocity for autonomous vehicles at high speed steering condition, the robust trajectory tracking control is studied. Firstly, the vehicle system models are established and the novel target longitudinal velocity planning is carried out. This velocity planning method can not only ensure that the autonomous vehicle operates in a strong nonlinear coupling state in bend, but also easy to be constructed. Then, taking the lateral location deviation minimizing to zero as the lateral control objective, a robust active disturbance rejection control path tracking controller is designed along with an extended state observer which can deal with the varying velocity and uncertain lateral disturbance effectively. Additionally, the feedforward-feedback control method is adopted to control the total tire torque, which is distributed according to the steering characteristics of the vehicle for additional yaw moment to enhance vehicle handing stability. Finally, the robustness of the proposed controller is evaluated under velocity-varying condition and sudden lateral disturbance. The single-lane change maneuver and double-lane change maneuver under vary longitudinal velocity and different road adhesions are both simulated. The simulation results based on Matlab/Simulink show that the proposed controller can accurately observe the external disturbances and have good performance in trajectory tracking and handing stability. The maximum lateral error reduces by 0.18 meters compared with a vehicle that controlled by a feedback-feedforward path tracking controller in the single-lane change maneuver. The lateral deviation is still very small even in the double lane change case of abrupt curvature. It should be noted that our proposed control algorithm is simple and robust, thus provide great potential for engineering application.*

***Keywords:*** *autonomous vehicle, path tracking, velocity tracking, active disturbance rejection control, robustness*

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## 1. Introduction

Intelligent vehicle technology has attracted increasingly attention with the rapid development of internet communication technology, computer artificial intelligence and other technologies (Wang et al., 2001). Autonomous vehicles are the most advanced of intelligent vehicles and will play an important role in reducing traffic accidents, saving energy and reducing emission (Hu et al., 2016; Wang et al., 2020). Motion control for trajectory tracking is one of the core issues in the field of autonomous vehicle research besides the environment perception, dynamic decision and planning. The most important thing is to obtain effective throttle, braking and steering action within the vehicle through trajectory tracking control (Amer et al., 2017).

The vehicle models should be established before the trajectory tracking control. Many vehicle models had been utilized in autonomous vehicle path tracking control. Van N. D. et al. studied the steering control of autonomous vehicles based on the pure pursuit model which was the most commonly used geometric model (Van et al., 2020). However, the geometric model was based on the Ackerman steering principle and could only be used in low-speed linear condition. The kinematic model was utilized for the trajectory planning and tracking in (Zhang et al., 2019), but the dynamic characteristics of the vehicle were not taken into account. The dynamic model (Zhao et al., 2011; Cai et al., 2018; Gao et al., 2018; Chen et al., 2019) had been widely used because it can be applied to the high-speed nonlinear condition, especially to the limit conditions.

Based on the vehicle dynamic model, the proportion-integral-derivative (PID) algorithm was utilized to control the yaw angle deviation approaching to zero and verified the effectiveness of the controller by real vehicle test (Zhao et al., 2011; Cai et al., 2018). However, PID controller is sensitive to the change of system parameters and the adaptability of the controller parameters to the vehicle speed is relatively weak. Hamilton energy function control could make the system achieve local or global optimization under some conditions such as automatic emergency obstacle avoidance (Gao et al., 2018,) and path tracking (Chen et al., 2019). However, the optimal control method relied on accurate mathematical model and cannot suppress the disturbance caused by the change of parameters and uncertain disturbance.

Since the autonomous vehicles often suffered by the internal parameter uncertainty and external disturbance, the robust control methods were widely used in trajectory tracking of autonomous vehicles. Model predictive control has been widely used in vehicle motion control (Sun et al., 2018; Cheng et al., 2020; Guo et al., 2020; Lin et al., 2019) owing to its good robustness, but it need to give consideration to the model accuracy, calculation complexity and real-time performance. A robust $H\infty$ state-feedback controller is proposed to achieve the path following and vehicle lateral control simultaneously (Wang et al., 2016). (Ardashir et al., 2020) proposed an adaptive control based on immersion and invariance control theorem for trajectory tracking of autonomous vehicles subject to uncertain dynamics. An adaptive neural-network-based steering controller was proposed for autonomous vehicle at handing limits which had good robustness against different road adhesion (Ji et al., 2018). Active disturbance rejection control (ADRC) also had been used in autonomous vehicle tracking control (Xia et al., 2016; Wu et al., 2019; Yan et al., 2019). The ADRC algorithm was established and developed by Jingqing Han et al (Han et al., 2002; Gao et al., 2013), and the stability analysis had been proved in (Wu et al., 2018). The ADRC can provide potentials to improve robustness by observing and compensating the modelling uncertainty and external disturbance. However, the construction of the desired yaw angle increases the difficulty of parameter adjustment, and the steady-state lateral deviation may occur when the parameters are not adjusted properly (Wu et al., 2019; Yan et al., 2019).

These control methods were all robustly, but few researches devoted to velocity-varying conditions. Nevertheless, vehicle longitudinal velocity varies when a car runs on a road, and the variable longitudinal velocity has a great impact on vehicle steering stability since the strong coupling dynamics exist between the longitudinal and lateral motion. Nam D. V. applied an adaptive pure pursuit-based steering controller besides a longitudinal controller and verified its robustness via real vehicle tests (Van et al., 2020). However, the robustness of high-speed conditions was not considered since the coupling of longitudinal and lateral motion was not strong with low longitudinal velocity and lateral acceleration. Nitin R. K. et al. designed a feedforward-feedback steering controller for both accurate path tracking and lateral stability at vehicle handling limits (Kapania et al., 2015). Nonlinear model inversion control was presented to control the position and sideslip of the autonomous vehicle approaching to the desired trajectory (Goh et al., 2019). Erik W. employed the State Dependent Riccati Equation technique to design a feedback-feedforward steering controller which showed robust path tracking performance even when the rear wheels reaches their friction limits, and large body sideslip prevails (Wachter et al., 2019). These papers (Kapania et al., 2015; Goh et al., 2019; Wachter et al., 2019) had considered the change of longitudinal velocity, and the control methods had been proved to be robust to different road curvature. However, the robustness to the unknown strong disturbances was not discussed. So the vehicle trajectory tracking control subject to both velocity-varying and uncertain disturbance at high speed is still worth to study.

In this paper, the uncertainty dynamics, external disturbances and the change of longitudinal velocity are considered simultaneously. The active disturbance rejection control (ADRC) with extended state observer (ESO) is used to control the lateral motion of the autonomous vehicle aiming at zero lateral deviation; the feedforward-feedback control method is used to control the longitudinal motion, so as to achieve the precise trajectory tracking of the autonomous vehicle under velocity-varying conditions. The main contributions of this paper are as follows:

(1) A new longitudinal velocity planning method is proposed to approach the adhesion limit at the maximum curve;
(2) The velocity tracking for autonomous vehicle is completed besides path tracking aiming at the high-speed emergency obstacle avoidance;
(3) To deal with the varying velocity and uncertain external disturbances, the extended state observer is employed in the controller design.

The rest of this paper is organized as follows. The system modelling and longitudinal velocity planning are presented in section II and section III. Section IV gives a detailed description about the trajectory tracking controller design. Section V presents the simulation verification of different control algorithm's performance and robustness. Section VI is the conclusion.

## 2. System Modelling

### 2.1. Vehicle dynamics model

In order to study the trajectory tracking performance of autonomous vehicle under the longitudinal and lateral coupling motions such as obstacle avoidance at high-speed, the planar motion stability is mainly considered than roll or pitch stability. Thus the impacts of suspension system and road inequality are ignored in this paper. So the three degrees of freedom vehicle model concluding longitudinal motion, lateral motion and yaw motion is established. Figure 1 shows the vehicle system model. In the figure, *OXY* is the absolute coordinate system, *oxy* is the vehicle coordinate system:

– $l_f$, $l_r$ are the distance from the vehicle centre of mass to the front axle and rear axle respectively;
– $\delta_f$ is the front wheel angle;
– $F_{yfl}$, $F_{yfr}$, $F_{yrl}$, $F_{yrr}$ are the lateral forces on the left front wheel, right front wheel, left rear wheel and right rear wheel respectively;
– $F_{xfl}$, $F_{xfr}$, $F_{xrl}$, $F_{xrr}$ are respectively the longitudinal forces on the left front wheel, the right front wheel, the left rear wheel and the right rear wheel;
– $v$ is the vehicle's centroid speed;
– $v_x$ is the vehicle's longitudinal speed at the centroid;
– $v_y$ is the vehicle's lateral speed at the centroid;
– $\beta$ is the vehicle's centroid sideslip angle;
– $w$ is the vehicle's yaw rate.

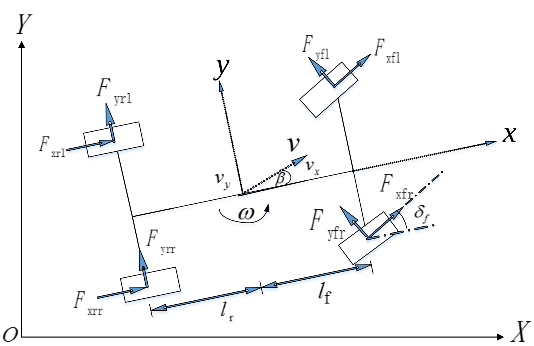



Fig. 1. Vehicle system model

$$\begin{cases} \dot{v}_x = v_y\dot{\psi} + (F_{xf}\cos\delta_f - F_{yf}\sin\delta_f + F_{xr})/m \\ \dot{v}_y = -v_x\dot{\psi} + (F_{xf}\sin\delta_f + F_{yf}\cos\delta_f + F_{yr} + F_{fw})/m \\ \dot{w} = (F_{xf}l_f\sin\delta_f + F_{yf}l_f\cos\delta_f - F_{yr}l_r + \Delta M)/I_z \\ \dot{Y} = v_x\sin\psi + v_y\cos\psi \\ \dot{X} = v_x\cos\psi - v_y\sin\psi \end{cases} \tag{1}$$

Where $X$ and $Y$ are the longitudinal and lateral displacement of the vehicle in $OXY$ coordinate; $\psi$ is the yaw angle of the vehicle ; $F_{yf}$, $F_{yr}$, $F_{xf}$, $F_{xr}$ are the lateral and longitudinal tire forces of front and rear axles respectively; $F_{fw}$ is the disturbance of uncertainty dynamic and external disturbances such as lateral wind; $m$ is the mass of the vehicle; $\Delta M$ is the additional yaw produced by the longitudinal force of the tires; $I_z$ is the yaw moment of inertia of vehicle.

## 2.2. Tire model

The main purpose of this paper is trajectory tracking control subject to velocity varying and uncertain disturbance. So the vehicle longitudinal and lateral coupled control will be studied in this paper. The nonlinear coupling of longitudinal and lateral tire forces is one of the main coupling influence factors besides the lateral-longitudinal-yaw motion coupling and vertical load transfer. The magic formula by H.B Pacejka prevails (Pacejka et al., 2006) is utilized to describe the coupling dynamics of tires.

The pure longitudinal and lateral tire forces can be calculated by the magic formula as follows:

$$\begin{aligned} F_{x0} &= D_x sin\,(C_x arctan\,(B_x s - E_x(B_x s - arctan(B_x s))) \\ F_{y0} &= D_y \sin\,(C_y \arctan\,(B_y\alpha - E_y(B_y\alpha - \arctan(B_y\alpha))) \end{aligned} \tag{2}$$

Where $s$ represents tire slip ratio; $\alpha$ is the sideslip angle. $C_x$=1.65; $C_y$=1.3; and according to (2):

$$\begin{aligned} D_x &= \mu(a_1F_z{}^2 + a_2F_z) \\ B_x &= (a_3F_z{}^2 + a_4F_z)\exp(-a_5F_z)/(C_xD_x) \\ E_x &= a_6F_z{}^2 + a_7F + a_8 \\ D_y &= \mu(b_1F_z{}^2 + b_2F_z) \\ B_y &= (b_3F_z{}^2 + b_4F_z)\exp(-b_5F_z)/(C_yD_y) \\ E_y &= b_6F_z{}^2 + b_7F + b_8 \end{aligned}$$

Where, $a_m$ and $b_n$ are fitting coefficients, $m$ and $n$ represent the number of 1 to 8; $F_z$ is the vertical force of the tire which can be expressed based on the roll dynamics and pitch dynamics; $\mu$ is the road adhesion coefficient.

In the combined longitudinal and lateral operation condition, the comprehensive slip ratio can be explained as equation (3)

$$\sigma = \sqrt{\sigma_x{}^2 + \sigma_y{}^2} \tag{3}$$

Where $\sigma_x = \frac{-s}{1+s}; \sigma_y = \frac{-\tan\alpha}{1+s}$.

Then, the combined longitudinal and lateral tire forces yield.

$$F_x = -\frac{\sigma_x}{\sigma}F_{x0}; F_y = -\frac{\sigma_y}{\sigma}F_{y0}c \tag{4}$$

Introducing the concept of equivalent lateral cornering stiffness (5), the tire model (2) can be simplified formally. The equivalent cornering stiffness is the real-time derivative of tire force to the tire sideslip angle, which is changeable at any time, and still conforms to the coupling nonlinear characteristics in (2).

$$\begin{cases} \hat{C}_f = \partial F_{yf}/\partial\alpha_f \\ \hat{C}_r = \partial F_{yr}/\partial\alpha_r \end{cases} \tag{5}$$

Where and represent the equivalent lateral cornering stiffness of front and rear axles, respectively.

The sideslip angel of front and rear wheels can be expressed as Equation (6) based on the small angle hypothesis.

$$\begin{cases} \alpha_f = -(\frac{v_y + wl_f}{v_x} - \delta_f) \\ \alpha_r = -\frac{v_y - wl_r}{v_x} \end{cases} \tag{6}$$

In order to introduce the tire torque to the controller design, the longitudinal tire fore can also be calculated as follows:

$$F_x = F_{xf} + F_{xr} = (-I_w(\dot{w}_f + \dot{w}_r) + T_w)/R_w \tag{7}$$

Where Tw is the sum of total driving torque and braking torque vector of front and rear axles; Iw represents the wheel yaw moment of inertia, Rw represents the wheel rolling radius, ωf and ωr are the angular velocity of front and rear wheels, respectively.

## 3. Longitudinal Velocity Planning

Currently, velocity planning had appears in lateral tracking under normal and extreme conditions (Goh et al., 2016, Guo et al., 2018, Wang et al., 2016; Kapania et al., 2016). The “quasi-equilibrium” strategy was used for a simple path generation and the reference sideslip angel was constructed as a function of path distance by aid of equilibrium point solution (Goh et al., 2019; Goh et al., 2016,). The reference velocity was yielded by solving the 3DOF vehicle dynamic equations under equilibrium states. However, not all paths are based on this "quasi-equilibrium" strategy. For a general path, the velocity planning generally falls into two categories. One is following the rule of decelerating entry in bends and accelerating out of the bends, but the speed and acceleration in initial positions and in bends can be set arbitrarily. This velocity profile construction method is simple and can be seen in (Guo et al., 2018, Wang et al., 2019). However, the velocity in any points does not approach the adhesion limit. Another method considers approaching the limit of adhesion, lateral stability criteria and the driving/braking actuator all the time (Kapania et al., 2016). Kapania N.R. took three steps to generate the velocity profile aimed at the minimum lap time: giving zero longitudinal force to plan velocity profile, then updating velocity profile after forward pass and backward pass. However, the path construction process is complex and should be re-planned because this profile was obtained based on the ideal steady state according to the reference path.

In this paper, the combination of the above two methods is adopted for a general path. On one hand, the reference longitudinal velocity and acceleration are designed according to the principle of slowing down before the start of the curve and accelerating after the curve. On the other hand, the velocity profile approaches the adhesion limit at the maximum curve location. This velocity-planning method can not only ensure that the autonomous vehicle operates in a strong nonlinear coupling state in bend, but also easy to be constructed.

### 3.1. Reference acceleration generation

The reference longitudinal acceleration is generated considering the road curvature and the comfort of passengers. Thus the longitudinal acceleration changes from zero, rather than braking suddenly with a large acceleration when autonomous vehicle enters in a curve. Since the velocity entering and leaving the curve is closely related to the curvature of the road, it is considered to express the expected longitudinal acceleration as a function of the road curvature, as shown in formula (8).

$$a_x{}^r = -\lambda \rho_r \operatorname{sign}(\dot{\rho}_r) \tag{8}$$

where $\lambda$ is a positive constant. The greater the constant is, the closer the vehicle reaches to the adhesion limit at the maximum bend.

### 3.2. Road information criteria

The longitudinal and lateral acceleration shall meet the adhesion conditions when the vehicle steers on the road.

$$\sqrt{a_x{}^2 + a_y{}^2} \leq \mu g \tag{9}$$

where $g$=9.8 $m/s^2$, ay represents vehicle lateral acceleration which can be calculated by longitudinal velocity and the road curvature as equation (11) shows.

$$a_y = \rho v_x{}^2 \tag{10}$$

## 4. Controller Design

### 4.1. Overall control strategy

Figure 2 shows the block diagram of the control system proposed in this paper. We take the front wheel angle, driving and braking torque of the tires as input of the autonomous vehicle ignoring the influence of steering system and traveling system.

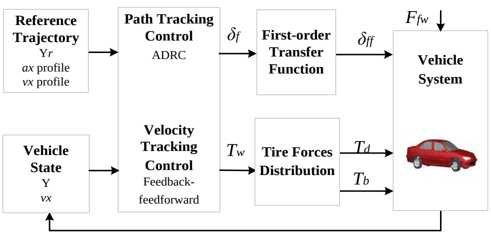



Fig. 2. The overall control frame

There are two parts of the control system and they interact with each other because of the vehicle vertical load transfer, the coupling of longitudinal and lateral tire force, and vehicle longitudinal-lateral-yaw motion coupling. Considering the time delay of the control system, a first-order delay link is introduced to simulate the front wheel angle delay of the control system, so as to avoid the instability or even vibration during the real vehicle control. In addition, additional yaw is generated to provide great potential for lateral stability through differential braking.

### 4.2. Lateral path tracking controller design

Substitute equation (6) and (7) into equation (1), the second derivative of Y can be calculated based on small angle hypothesis.

$$\begin{aligned}\ddot{Y} &= \dot{v}_x \sin\psi + \dot{v}_y \cos\psi + \dot{X}\dot{\psi} \\ &= \left(\frac{\hat{C}_f}{m} + \frac{T_w - I_w \dot{w}_f}{mR_w}\right)\delta_f - \frac{v_y(\hat{C}_f + \hat{C}_r) + \dot{\psi}(\hat{C}_f l_f - \hat{C}_r l_r)}{m v_x} \\ &\quad - v_x \dot{\psi} + \dot{v}_x \psi + \dot{X}\dot{\psi} + \frac{F_w}{m}\end{aligned} \tag{11}$$

Since the coefficient of front wheel angle contains input $T_w$ and state variable $\dot{w}_f$, which are time-varying. Thus, constant $b$ and variable $b_w$ are introduced, and the relationship is as follows:

$$b_w + b = \frac{\hat{C}_f}{m} + \frac{T_w - I_w \dot{w}_f}{mR_w} \tag{12}$$

Take time-varying as disturbance, and Equation (11) can be rewritten as follows:

$$\begin{aligned}& Y = x_1, \dot{Y} = x_2, \ddot{Y} = \dot{x}_2, \\ & f_w = b_w \delta_f - \frac{v_y(\hat{C}_f + \hat{C}_r) + \dot{\psi}(\hat{C}_f l_f - \hat{C}_r l_r)}{m v_x} \\ & - v_x \dot{\psi} + \dot{v}_x \psi + \dot{X}\dot{\psi} + \frac{F_w}{m}\end{aligned} \tag{13}$$

Equation (4) can be expressed as the standard form of integrator series system:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = b\delta_f + f_w \\ y = x_1 \end{cases} \tag{14}$$

Where $f_w$ is the sum of uncertain dynamics and unknown disturbances of the system; $y$ is the output of the system.

In this paper, active disturbance rejection control (ADRC) is utilized to observe and compensate the modelling uncertainty and external disturbance, and then make the autonomous vehicle track the reference path.

The whole ADRC consists of three modules: tracking differentiator (TD), nonlinear combination law (NCL) and extended state observer (ESO). TD is utilized to extract a smooth input signal and its differential signal; ESO provides potentials for the observing and compensating of the un-modeled dynamic and unknown disturbance; NCL takes the output error between ESO and TD to determine the control output. The control frame of the ADRC is shown in Figure 3.

The tracking differentiator utilizes the "fast control optimal synthesis function" to track the reference differential signal rapidly, which avoids extracting derivatives from the tracking error. The total disturbance is taken as the expanded state variable in the design of extended state observer, and the uncertain system is dynamically linearized in real time. Then, the un-modelled dynamic and unknown disturbance can be observed and compensated. The nonlinear combination part uses output error between TD and ESO to determine the control output $\delta_{f0}$ and uses the estimated value of the disturbance to compensate system in order to obtain the final control output $\delta_f$.

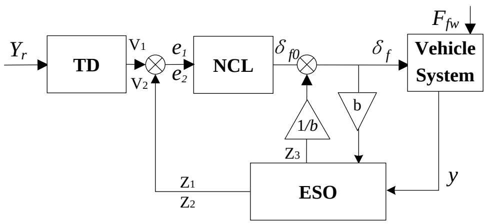



Fig. 3. Lateral path tracking ADRC controller

#### 4.2.1. TD

The discrete form of system (14) is:

$$\begin{cases} x_1(k+1) = x_1(k) + hx_2(k) \\ x_2(k+1) = x_2(k) + hu, |u| \le r \end{cases} \tag{15}$$

The fast control optimal synthesis function obtained from the above formula is as follows:

$$\begin{cases} d = rh; d_0 = dh \\ c = x_1 + hx_2 \\ a_0 = (d^2 + 8r|c|^{1/2}) \\ a = \begin{cases} x_2 + (a_0 - d)/2 & |c| > d_0 \\ x_2 + c/h & |c| \le d_0 \end{cases} \\ u = -\begin{cases} ra/d & |a| \le d \\ r\mathrm{sgn}(a) & |a| > d \end{cases} \end{cases} \tag{16}$$

Where, $h$ is the simulation integration step, and 0.001$s$ is taken in this paper; the controller design parameter $r$ represents the speed factor, which determines the tracking speed and is generally selected with a larger value.

#### 4.2.2. ESO

Set $x_3 = f_w, \dot{x}_3 = g_w$.
Take $f_w$ as a new state variable $x_3$ assuming that $f_w$ is bounded and can be differentiated into $g_w$, then the equation (6) can be expanded into the control system as follows:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = b\delta_f + f_w \\ y = x_1 \end{cases} \quad (17)$$

Set the output of the state observer as $z_1$ 、 $z_2$ and $z_3$, which are the observation values of y、$\dot{y}$and $f_w$ respectively. Then, the observation error of the system output is:

$$e = z_1 - y \quad (18)$$

The state equation of the observer is shown in equation (19).

$$\begin{cases} \dot{z}_1 = z_2 - \beta_1 e \\ \dot{z}_2 = b\delta_f + z_3 - \beta_2 fal_1(e, \alpha_1, \delta) \\ \dot{z}_3 = -\beta_3 fal_2(e, \alpha_2, \delta) \end{cases} \quad (19)$$

where:

$$\beta_1 = 3w_0, \beta_2 = 3w_0^2, \beta_3 = 3w_0^3 \quad (20)$$

$$\begin{cases} fal_1 = \begin{cases} |e|sign(e) & |e| \geq \delta \\ \frac{e}{\delta^{(1-\alpha_1)}} & |e| < \delta \end{cases} \\ fal_2 = \begin{cases} |e|sign(e) & |e| \geq \delta \\ \frac{e}{\delta^{(1-\alpha_2)}} & |e| < \delta \end{cases} \end{cases} \quad (21)$$

Where, $w_0$ can be seen as the wideband of the observer which affects the observer tracking speed significantly. The accuracy of the estimation is positively related to the value of $w_0$. However, the noise sensitivity may increase if the observer bandwidth is too large. An appropriate value of $w_0$ can estimate total disturbance $z_3$ accurately tracking $f_w$. The observer can converge when the observer wideband is expressed as formula (11) (Wu et al., 2018). $\alpha_1, \alpha_2, \delta$ is the controller design parameters, the general selection range is $\alpha_2 < \alpha_1$, which can be taken as $\alpha_1 = 0.5, \alpha_1 = 0.25$ (Han et al., 2002).

#### 4.2.3. NCL

Assuming the output and its differential signal after the TD are $v_1$ and $v_2$ respectively, the deviation between the TD output and the ESO output will be:

$$\begin{cases} e_1 = v_1 - z_1 \\ e_2 = v_2 - z_2 \end{cases} \quad (22)$$

The nonlinear PD control law is designed by using the characteristic of *fal* function as equation (14).

$$\delta_{f0} = k_p fal_3(e_1, \alpha_3, \delta) + k_d fal_4(e_2, \alpha_4, \delta) \quad (23)$$

In the formula (23), the *fal* function is the similar as (21), in which the general selection range of $\alpha_3, \alpha_4$ is $0 < \alpha_3 \leq 1 \leq \alpha_4$ (Han et al., 2002); *kp* and *kd* are the design parameters, which are selected by experience.
Then, the lateral controller input can be expressed as equation (24) which can similarly linearize the system as system (25). This is the real-time dynamic linearization of uncertain systems.

$$\delta_f = \delta_{f0} - z_3/b \quad (24)$$

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = b\delta_{f0} \\ y = x_1 \end{cases} \quad (25)$$

### 4.3. Longitudinal velocity tracking controller

The longitudinal velocity controller is carried out in the way of feedforward and feedback control, as shown in Figure 4.

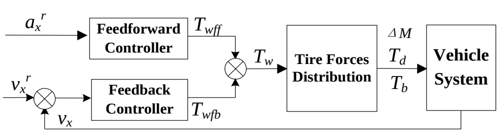



Fig. 4. Longitudinal velocity tracking feedback-feedforward controller

#### 4.3.1. Feedforward controller

Based on Newton's second law, the feedforward longitudinal torque of tires can be calculated since the reference longitudinal acceleration is known. Substitute equation (6) and the references into equation (1):

$$\dot{v}_x^{ref} = v_y\dot{\psi} + ((-I_w(\dot{w}_f + \dot{w}_r) + T_{wff}) / R_w - F_{yf} \sin\delta_f) / m \quad (26)$$

Where, $T_{wff}$ represents the feedforward tire torque and can be explained as the following equation (27).

$$T_{wff} = \left(m\dot{v}_x{}^{ref} - mv_y\dot{\psi} + F_{yf}\sin\delta_f\right)R_w + I_w(\dot{w}_f + \dot{w}_r) \quad (27)$$

#### 4.3.2. Feedback controller

Since the longitudinal velocity profile is designed in Section 2, a feedback controller is designed based on the error between the reference and actual longitudinal velocity.

If the desired longitudinal speed of intelligent vehicle is $v_x^r$ and proportional feedback control is adopted, the feedback tire torque $T_{wfb}$ is:

$$T_{wfb} = k(v_x^r - v_x) \quad (28)$$

Where, $T_{wfb}$ represents the feedback tire torque; $v_x^r$ is desired longitudinal velocity; $k$ represents the proportional factor.

Adding the feedforward tire torque (27) and feedback tire torque (28) yields the total tire torque $T_w$.

$$T_w = T_{wff} + T_{wfd} \quad (29)$$

#### 4.3.3. Tire torque distribution

Ignoring the modelling of engine and transmission systems, it is assumed that the driving torque and braking torque are directly applied to the tires. Thus Tw is treated as driving torque when $T_w>0$, and as braking torque contrarily when $T_w<0$. Assuming rear tires are the driving tires when in drive mode.

The additional yaw moment can provide potentials to improve lateral stability of the autonomous vehicle (Wu et al., 2017; Cheng et al., 2020). Therefore, the tire torque distribution is adopted to generate additional yaw moment for vehicle stability, while meeting the longitudinal force demand to ensure the speed tracking.

The additional yaw moment yielded by the braking torques can be calculated as following:

$$\Delta M = \frac{\sum(-1)^{i+1}T_{bi}S_{bi}}{R_w} \quad i = 1,2,3,4 \quad (30)$$

Where, the $S_{bi}$ denotes horizontal distance between the four wheels and the vehicle centroid, $T_{bi}$ represents the braking torque of the four wheel, and $i$ denotes the front axle left wheel, front axle right wheel, rear axle left wheel, rear axle right wheel respectively. The braking torque is distributed according to the steering characteristics of the vehicle which can be characterized by stability factor $K$.

$$K = \frac{m}{(l_f+l_r)^2}\left(\frac{l_f}{\hat{C}_r} - \frac{l_r}{\hat{C}_f}\right) \quad (31)$$

The vehicle is over-steer when $K$ is less than zero, and the vehicle is under-steer when $K$ is above zero. The single wheel braking strategy can be explained as table 1 (Yu et al., 2007).

Table 1. The tire torques distribution strategy

| Tire torques distribution strategy | Working condition |
|---|---|
| $T_{drl}=T_{drr}=0.5T_w$, $T_{dfl}=T_{dfr}=0$ | $T_w>0$ |
| $T_{b2}=-T_w$, $T_{b1}=T_{b3}=T_{b4}=0$ | $T_w<0$, turn left, $K<0$ |
| $T_{b1}=-T_w$, $T_{b2}=T_{b3}=T_{b4}=0$ | $T_w<0$, turn right, $K<0$ |
| $T_{b3}=-T_w$, $T_{b1}=T_{b2}=T_{b4}=0$ | $T_w<0$, turn left, $K>0$ |
| $T_{b4}=-T_w$, $T_{b1}=T_{b2}=T_{b3}=0$ | $T_w<0$, turn right, $K>0$ |

## 5. Simulation Results

In order to verify the -robustness of our proposed trajectory tracking controller subject to velocity-varying and external disturbance, a 10 DOF vehicle body and tire system model is established by Matlab/Simulink, and the simulation verification of different working conditions is carried out. The main parameters of the autonomous vehicle are shown in Table 2. The controller parameters are as follows: $r$ = 10000; $\alpha_3$ = 0.75; $\alpha_4$ = 1.5; $w_0$ = 10; $b$ = 83; $k_p$ = 0.01; $k_d$ = 12; $k$ = 40

The results of the proposed robust ADRC algorithm are compared with the feedback-feedforward steering controllers in (Kapania et al., 2015). The traditional heading deviation Δφ and amended heading deviation Δφ+β are set as control targets separately, we name the feedback-feedforward steering controllers as "FB-FF controller with Δφ" and "FB-FF controller with Δφ+β" accordingly. The constant cornering stiffnesses and real sideslip angle are used for calculation of the surveyed controllers. The design parameters of the surveyed controllers are as follows: $K_P$ = 0.6, $x_I$ = 20.

Table 2. Main vehicle parameters

| Parameters | Symbol | Value | Units |
|---|---|---|---|
| Vehicle mass | $m$ | 1515 | $kg$ |
| Yaw inertia | $I_z$ | 1680 | $kg.m^2$ |
| Distance between front axle to vehicle centroid | $l_f$ | 1.209 | $m$ |
| Distance between rear axle to vehicle centroid | $lr$ | 1.553 | $m$ |
| Nominal front axle cornering stiffness | $C_f$ | -118000 | $N/rad$ |
| Nominal rear axle cornering stiffness | $C_r$ | -108000 | $N/rad$ |

### 5.1. Single-Lane Change Maneuver

In the simulation, a single-lane change maneuver similar with that in (Wang et al., 2016) is completed for the vehicle at the initial speed of 30 m/s on the low-adherence road (μ = 0.2) while suffering from a strong lateral disturbance at t = 3.5s to t = 4.5s as Figure 5 shows. The lateral disturbance such as strong wind plays a significant role in road safety which may be affected the moving vehicle thus resulting sideslip (Betkier et al., 2019). The max lateral wind is set as 1000N which is twice that mentioned in reference (Shirazi et al., 2018). Figure 6(a) shows the road curvature varying with the vehicle travel distance. The reference longitudinal acceleration is plotted in Figure 6(b) from which one can see that the absolute value of longitudinal acceleration at the maximum curvature is the largest.

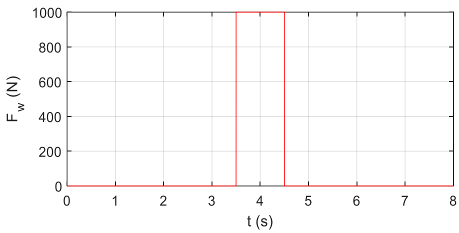
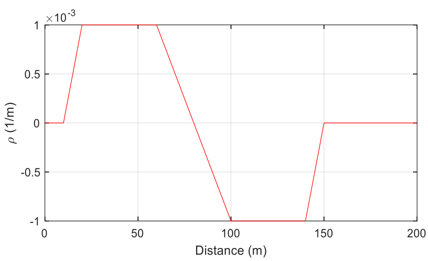
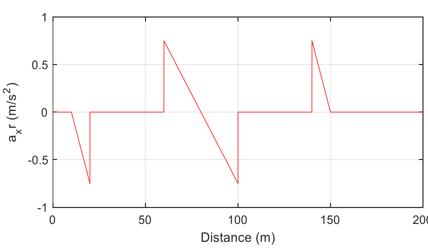



Fig. 5. Sudden lateral disturbance




**(a)**



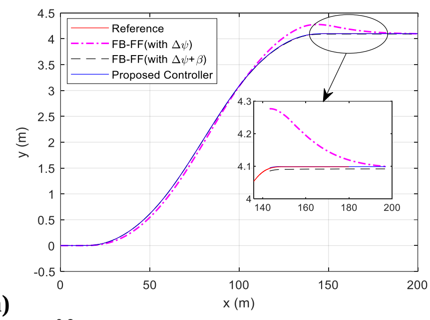

**(b)**

Fig. 6. Reference road curvature and longitudinal acceleration in single-lane maneuver: **(a)** Reference road curvature; **(b)** Reference longitudinal acceleration

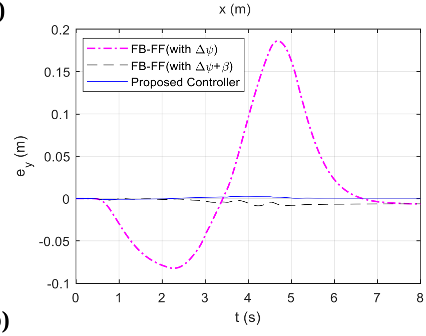
Figure 7.A. and 7.B. shows the trajectory tracking results with the proposed controller and surveyed controllers. Figure 7.A. (a)-(b) and 7.B. (c)-(d) present vehicle global displacement, lateral offset, traditional vehicle heading error, and amended velocity heading error respectively. It can be seen that the lateral offset of FB-FF controller based on vehicle heading deviation Δφ is much larger than the other controllers. The FB-FF controller based on amended velocity heading deviation Δφ+β provides great potential for reducing lateral displacement deviation and velocity heading deviation. However, the proposed controller performs best on path tracking errors. The max absolute deviation and integral time-weighted absolute error (Zhao et al., 2011) of the lateral displacement and vehicle heading deviation with different controllers are shown in Table 3.

Table 3. Tracking error comparison of different controllers

| Controller | Max($e_y$) | ITAE($e_y$) |
|---|---|---|
| FB-FF controller with Δφ | 0.1860 | 1.701 |
| FB-FF controller with Δφ+β | 0.0086 | 0.179 |
| Proposed controller | 0.0023 | 0.034 |

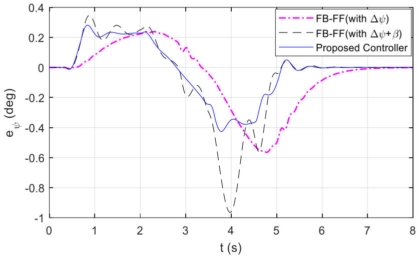



**(a)**

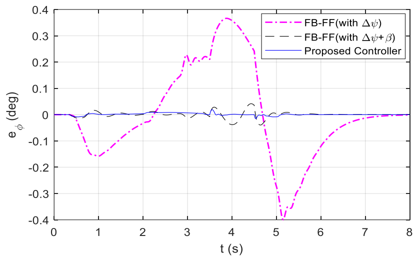



**(b)**

Fig. 7.A. The path following trajectory and tracking errors results in single-lane maneuver. **(a)** Path following trajectory results; **(b)** Lateral offset results



(c)

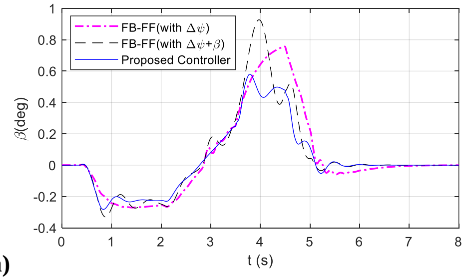


(d)

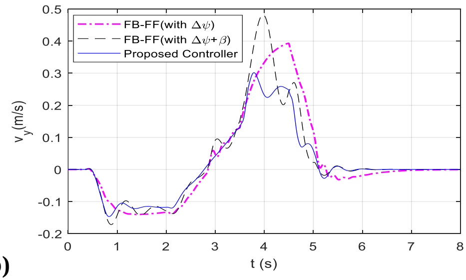
Fig. 7.B. The path following trajectory and tracking errors results in single-lane maneuver. **(c)** Vehicle heading error results; **(d)** Velocity heading error results

The sideslip angle, lateral velocity and acceleration are shown in the Figure 8, we can see that the proposed controller can yield minimum responses and maintain them in the more stability regions. The lateral acceleration of the proposed controller responds fast when suffering a sudden lateral disturbance at t = 3.5s and t = 4.5s, and the sideslip angle, yaw rate, lateral velocity increase when the external disturbance is introduced. The FB-FF controller with Δφ is dedicated to eliminating yaw angle deviation, thus yield smooth yaw rate response as sub-figure (d) shows.

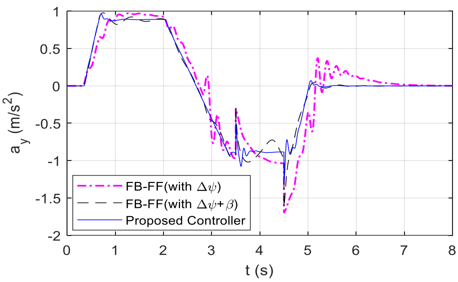
The longitudinal velocity and the corresponding control input total tire torque are plotted in Figure 9, from which we can see that changing trends of the tire torque are much similar as that of reference longitudinal acceleration, and the longitudinal velocity can vary roughly with the expected value. Figure 10 shows the simulation results of the front-wheel steering angle. It can be seen that the front-wheel steering angle controlled by the proposed controller changes with the road curvature roughly. The front-wheel steering angle just increases intense in the initial and final moments of lateral disturbance, and the overall performance is better than that of FB-FF controllers.



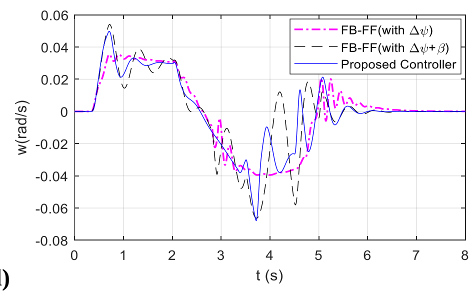
(a)



(b)



(c)



(d)

Fig. 8. The simulation results for the sideslip angle, lateral velocity, acceleration and yaw rate in the single-lane change maneuver. **(a)** Sideslip angle; **(b)** Lateral velocity; **(c)** Lateral acceleration; **(d)** Yaw rate

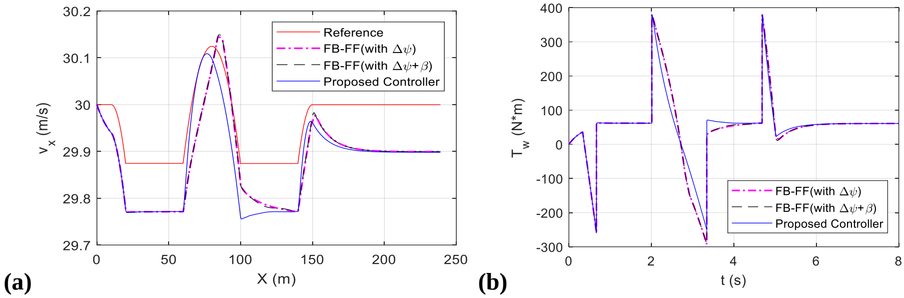



Fig. 9. The simulation results for the longitudinal velocity and control inputs in single-lane change maneuver. **(a)** Longitudinal velocity; **(b)** Total tire torques

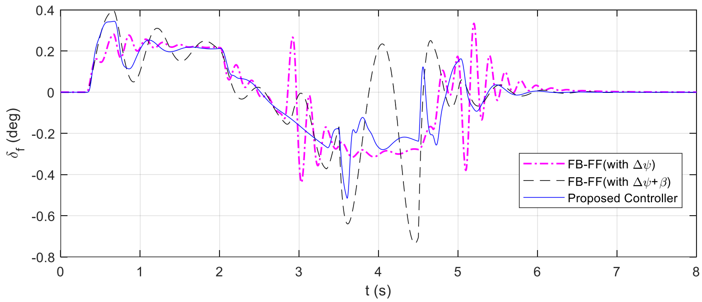



Fig. 10. The simulation results for the front-wheel steering angel in single-lane change maneuver

In addition, the single-lane change maneuver (Wang et al., 2016) on bigger curve road of different controllers is also compared. The road curvature is plotted in Figure 11(a), which is three times larger than that mentioned above. The vehicle is required to run on the high-adherence road (μ = 0.8) with initial speed of 30 m/s. The simulation results are similar with that on smaller curve road, only parts of them are shown in the paper due to length limitations. One can see from Figure 11 that the autonomous vehicle with three controllers can track the reference path and velocity approximately, but the vehicle equipped with the proposed controller performs best.

### 5.2. Double-Lane Change Maneuver

In this simulation case, the double-lane change maneuverer is performed on a high-adherence road μ = 0.8, with the initial speed of 22m/s. The lateral disturbance is the same as Figure 5 shows. The road curvature varying with the vehicle travel distance is presented in Figure 12(a). Figure 12(b) shows the reference longitudinal acceleration, which grows to maximum at the biggest curve similarly.

The tracking errors, vehicle states response, and control inputs with different controllers are shown in Figure 13. Similarly, as shown in sub-figure (a)-(d), the FB-FF controller with Δφ performs best in the vehicle heading error response, nevertheless, yields large lateral offset and velocity heading deviation. The maximum lateral deviation is nearly 0.4m and the maximum velocity heading deviation is about 2deg, however, that of the FB-FF controller with Δφ+β and the proposed controller can be maintained in a very small region. In contrast, the proposed controller performs best in path tracking.

Figure 14 shows the sideslip angel, lateral velocity, acceleration and yaw rate of the vehicle. It can be seen that all of the three controllers are able to keep the autonomous vehicle in stability regions after the lateral disturbance is introduced into the system. One can see that the proposed controller has the better performance than the FB-FF controller with Δφ+β in the level of vehicle states, which guarantees more lateral stability of the vehicle. The FB-FF controller with Δφ can yield smaller response of vehicle dynamics, however the increase of tracking errors is much larger compared with the decrease of state deviations.

As shown in Figure 15 which plots the longitudinal velocity and the total tire torque that, no matter what kind of control mode is implemented, the tire torques change with the reference lateral acceleration roughly, and the tracking errors of longitudinal velocity keep the same basically. The front-wheel steering angle is plotted in Figure 16, the analysis of the front-wheel steering angle is consistent with that of the vehicle states. On the whole, the proposed controller performs best in tradeoff of trajectory tracking and lateral stability.

Moreover, the double-lane change maneuver with more sharp corners shown in (Wang et al., 2016) is completed for the vehicle. The road adhesion coefficient is set as μ = 0.6 and the initial longitudinal velocity is 25m/s. Similarly, it can be seen from the Figure 17 that three controllers can yield reasonable path tracking and velocity tracking errors, among which the proposed controller performs best in trajectory tracking.

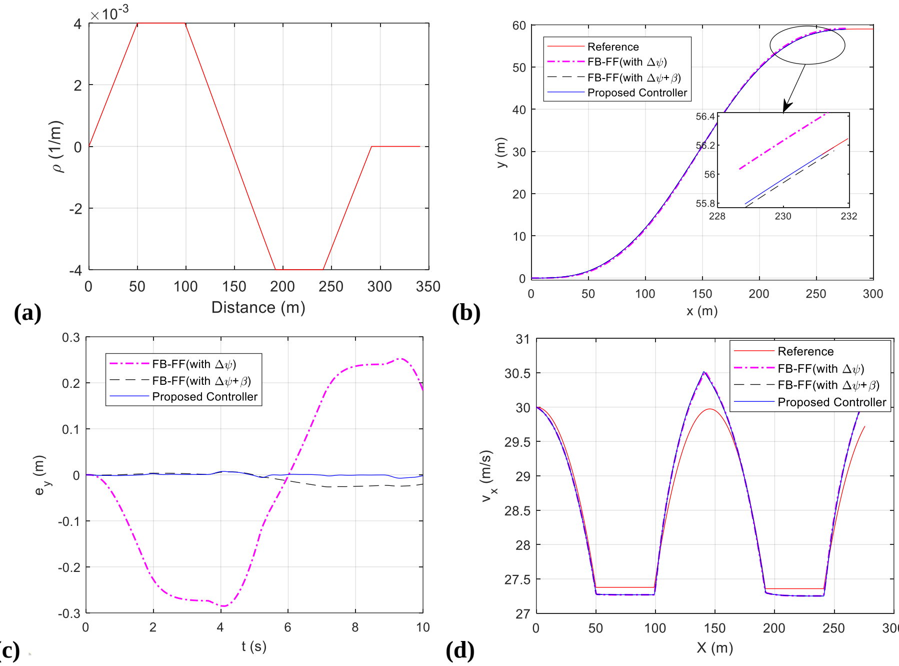



Fig. 11. The simulation results in the single-lane change maneuver on bigger curve road. **(a)** Road curvature; **(b)** Global displacement; **(c)** Lateral offset; **(d)** Longitudinal velocity

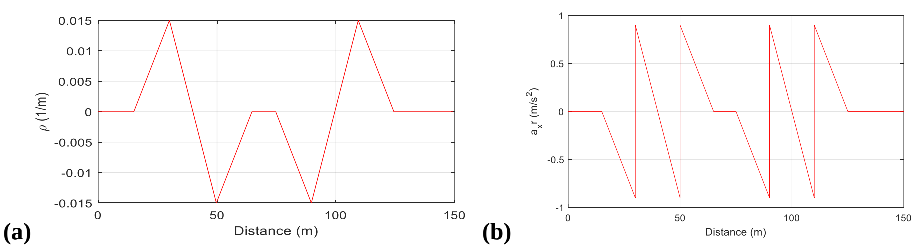



Fig. 12. Reference road curvature and longitudinal accelerations in double-lane maneuver. (a) Reference road curvature; (b) Reference longitudinal acceleration

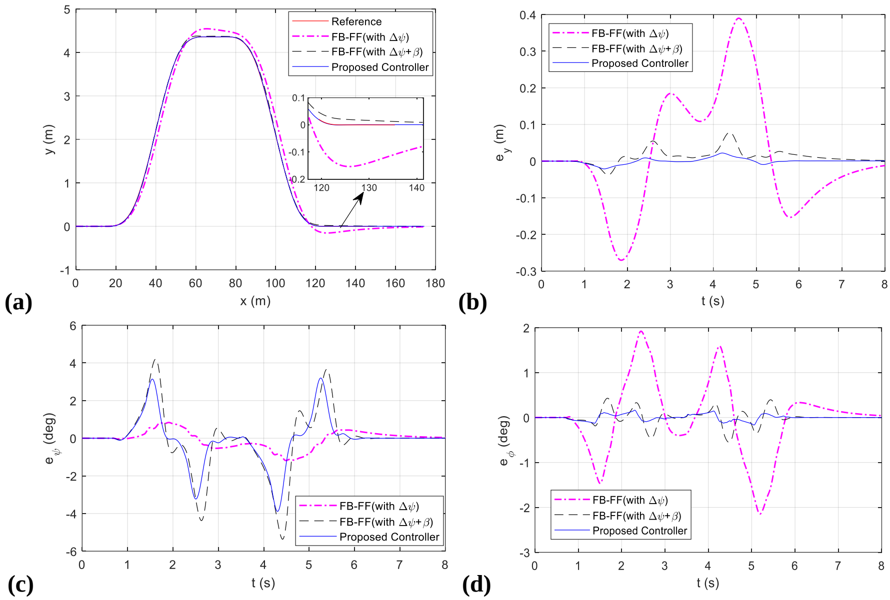



Fig. 13. The path following trajectory and tracking errors results in double-lane maneuver. (a) Path following trajectory results; **(b)** Lateral offset; **(c)** Vehicle heading error; **(d)** Velocity heading error

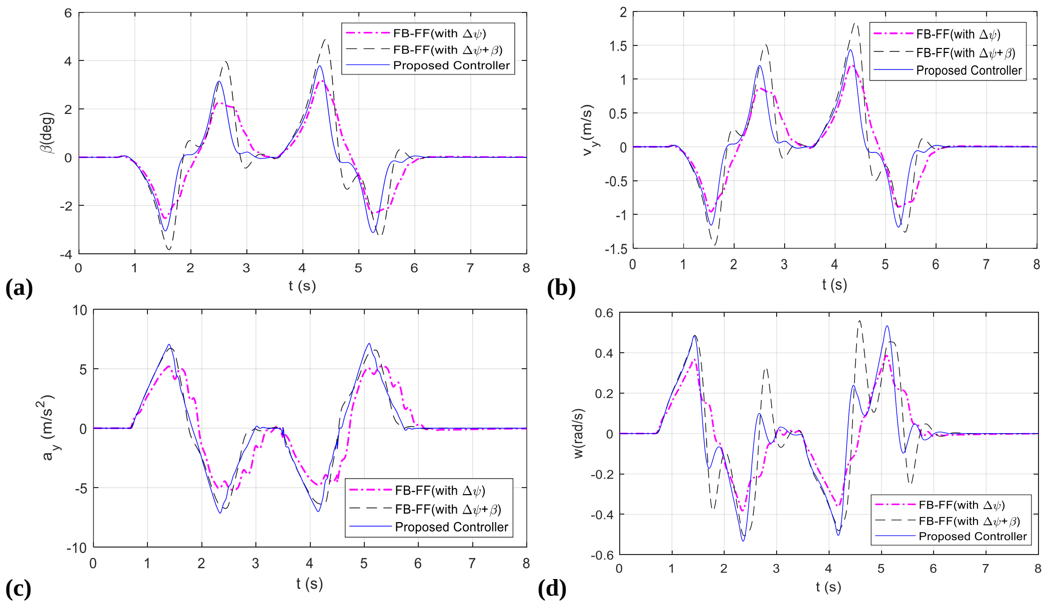



Fig. 14. The simulation results for the sideslip angle, lateral velocity, acceleration and yaw rate in the double-lane change maneuver. **(a)** Sideslip angle; **(b)** Lateral velocity; **(c)** Lateral acceleration; **(d)** Yaw rate

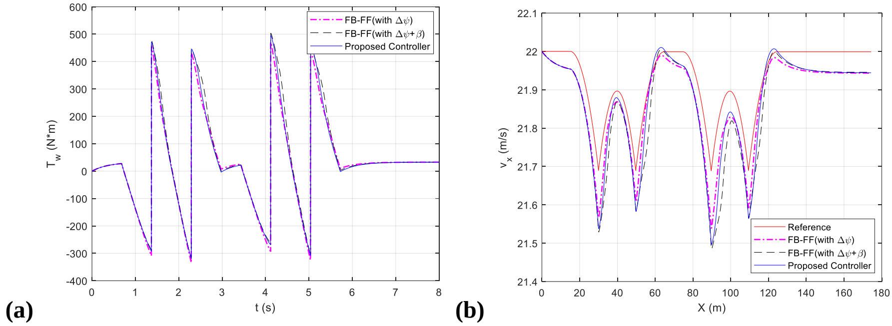



Fig. 15. The simulation results for the longitudinal velocity and control inputs in double-lane change maneuver. **(a)** Longitudinal velocity; **(b)** Total tire torques

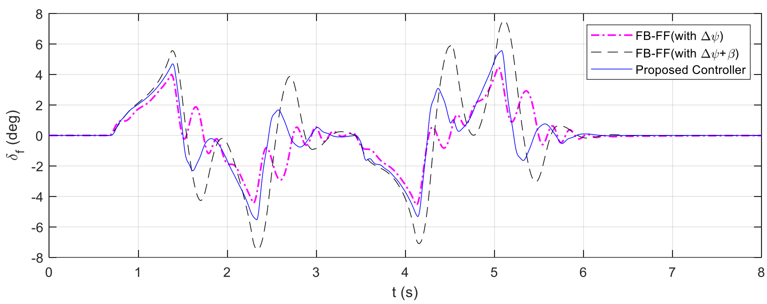



Fig. 16. The simulation results for the front-wheel steering angel in double-lane change maneuver

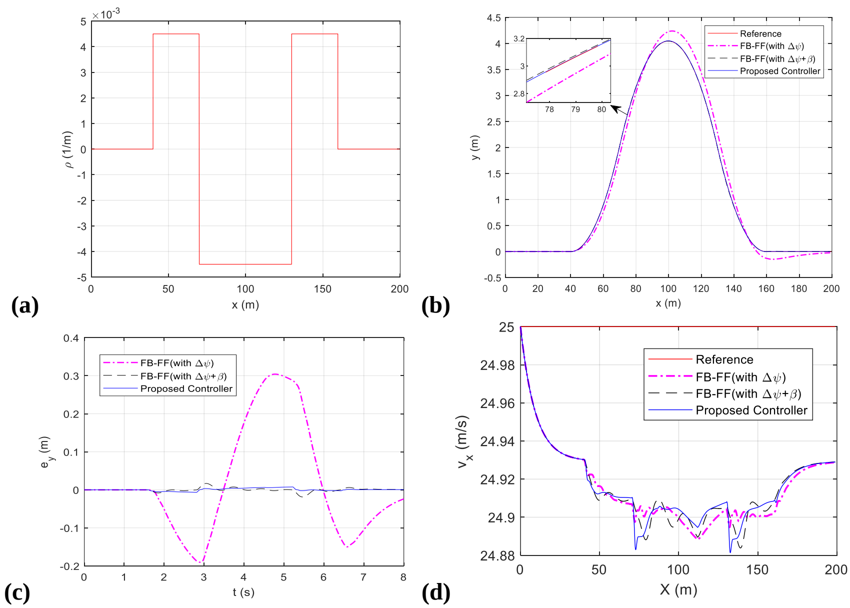



Fig. 17. The simulation results in the double-lane change maneuver with more sharp corners. **(a)** Road curvature; **(b)** Global displacement; **(c)** Lateral offset; **(d)** Longitudinal velocity

## 6. Conclusion

This paper proposed a robust trajectory tracking control algorithm for autonomous vehicle subject to velocity-varying and uncertain disturbance. The trajectory tracking includes two aspects: lateral path tracking and longitudinal velocity tracking before which a new reference longitudinal velocity planning method is proposed. The ADRC lateral path tracking controller and the feedforward-feedback longitudinal velocity tracking controller were designed and verified through MATLAB/Simulink. The proposed controller in this paper can accurately observe and compensate the lateral disturbance robustly and performs best in tradeoff of trajectory tracking and lateral stability.

It should be noted that our proposed control algorithm is simple and robust, thus provide great potential for engineering application. In the future, we will further carry out hardware in the loop test and real vehicle test for the proposed control algorithm.

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# ASSESSMENT OF OPTIONS TO MEET TRANSPORT NEEDS USING THE MAJA MULTI-CRITERIA METHOD

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***Abstract:***

*The problem of choosing the way to move people is often encountered both in scientific research and in everyday life. The difficulty of this process depends on the availability of many variants and the pursuit of satisfying transport needs at the minimum cost, in the shortest possible time and in the most comfortable conditions. The publication presents a decision problem of choosing the best transport option using multi-criteria methods. At the beginning authors presented the widely used methods of solving decision problems in the literature. Subsequently, based on the example of the Warsaw-Wroclaw connection, the MAJA multi-criteria assessment method algorithm was analysed. Both road, rail and air transport options were considered. Six possible variants of solutions were indicated, which were assessed in three sub-criteria: cost, time and comfort of travel. Then, the results of the analysis were compared with the results obtained using other multi-criteria decision-making support methods, i.e. ELECTRE I, AHP, TOPSIS, PROMETHEE, SAW, PVM. The considered methods were divided according to the way the result was presented, as a result of which the methods based on the relation of superiority (which included the MAJA method) and methods using ranking were distinguished, and then an intra-group comparison was made. On the basis of the constructed compliance matrix of the relation of superiority, it was found that domination methods exhibited convergence of the obtained results. However, in order to compare the convergence of the results of the ranking methods, the Spearman's linear correlation coefficient was used. The applied MAJA multi-criteria method has made it possible to determine non-dominated solutions considered optimal taking into account the adopted weights of criteria and compliance and non-compliance thresholds. Its unquestionable advantage is the possibility of using many partial criteria expressed in different measurement units. In the presented example, the best options were the premium express rail transport and airplane. The summary defines the direction of further research and possibilities of modification of the presented method.*

**Keywords:** *transport, multi-criteria method, optimization, decision problem*

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## 1. Introduction

The problem of selection and classification of solution options is often encountered in many areas, including logistics and transport. A multi-criteria decision problem is one in which, having a defined set of possible options and a coherent range of criteria, an attempt is made to define a subset of options considered to be the best in relation to the considered range of criteria (selection problem), to divide the set of decisions into subsets according to certain standards (sorting problem) or to rank the set of decisions from the best to the worst (arranging or ranking problem) (M. Jacyna et al., 2018; Wasiak et al., 2017). In the decision-making process, one of the most important actions is to select an appropriate multi-criteria research method (M. Jacyna and Semenov, 2020; Sun et al., 2018).

The methods of multi-criteria assessment have been divided into four groups according to the current literature: mathematical, geometric, taxonomic and quantitative. In practice, mathematically advanced assessment methods, such as ELECTRE (fr. ELimination Et Choix Traduisant la REalité) (ELimination and Choice Expressing REality) (Hwang and Masud, 1979), AHP (Analytic Hierarchy Process), TOPSIS (Technique for Order Preference using Similarity to Ideal Solution), PROMETHEE (Preference Ranking Organization METHod for Enrichment of Evaluations), SAW (Simple Additive Weighting) and PVM (Preference Vector Method), see the most use.

ELECTRE encompasses a set of multi-criteria methods developed by European scholars since the 1960s. The methodological basis of this method sets the minimum number of criteria considered at three. In practice, however, a set of five or more assessment criteria of heterogeneous character is most often used. In order to accurately map the analysed decision problem, preference and equivalence threshold values were introduced (Izdebski, Jacyna-Gołda, Gołębiowski, Pyza, et al., 2020; Kahraman, 2008). The aim of such an approach is to build an exceeding order based on a set of decision making options, which is a partial order of global preference. This approach leaves room for a situation of non-comparability of the options, justifying this, for example, by the lack of sufficient information to determine the preferential situation. In a case where the choice between the two options does not matter, there is indifference (Srinivas and Deb, 1994). The publication (Bojković et al., 2010) uses the ELECTRE I method to assess transport systems in CEE countries in terms of sustainability. A methodological modification leading to control and avoidance of indifference relations between variants has been proposed. The authors of the article (Kiciński and Solecka, 2018) used the ELECTRE III and AHP method to evaluate and select the optimal solution in the area of urban public transport on the example of Cracow. Seven decision-making options were analysed against ten evaluation criteria, including cost, time and travel standard.

The AHP method, presented by Thomas L. Saaty, is based on mathematical calculations taking into account the influence of the human psyche and preferences (Saaty, 1990). The result of such an approach is a multi-faceted approach to the issue of the decision-making task, leading to the determination of the significance of individual assessment criteria (Dong et al., 2010; Vidal et al., 2010). The AHP method comes down to the following steps (Wei et al., 2005):

– creation of a hierarchical model (i.e. analysis of the decision-making problem with pointing out the considered criteria);
– comparative assessment of criteria and options by means of a relative scale of dominance;
determination of local and global preferences (i.e. validity of criteria and decision-making options);
– classification of decision-making options.

In the field of transport, the AHP method has been implemented to evaluate solutions in the area of urban transport (Kiciński and Solecka, 2018; Orman et al., 2018), development of transport infrastructure (Ayyyildiz and Taskin Gumus, 2020; Kaya et al., 2020), railway transport safety (Sangiorgio et al., 2020) and choice of means of air transport (Kiracı and Akan, 2020).

The TOPSIS was presented by K. Yoon and C.L. Hwang and is based on the concept of aggregation with a synthetic criterion, removing the non-comparability of the options by means of non-compensatory logic. It strives to organize the analysed options on the basis of determining the distance from the ideal or anti-ideal solution. The best option is the one that is closest to the ideal solution (farthest from the anti-ideal solution). It applies to the assessment and classification of sets of the same type of options (J. Wu and Chung, 2005). TOPSIS was used in the publication (Liu et al., 2020) to minimise risk in the logistics activities of companies. Another example of the implementation of the method is the article (Kumar et al., 2020), in which the authors evaluated the fuels used to run a diesel engine. The fuel mixture obtained as a result of the conducted research improved engine performance and reduced emissions and fuel costs.

PROMETHEE is a multi-criteria method of decision support, consisting in establishing a ranking of considered options. The essence of the PROMETHEE method is a comparison of alternative options within each criterion under consideration. The ease of the computational algorithm prompts authors of scientific publications to implement it in many areas of research. The paper (Sarraf and McGuire, 2020) compares multi-criteria decision-making methods to help decision-makers choose the best route from all available routes. As a result, the convergence of results obtained using PROMETHEE and AHP methods was shown. Another example of using the PROMETHEE method is the publication (Lin et al., 2020), which assesses the economic, social, cultural and environmental impact of tourism on the example of Hainan. As a result of the analysis of five scenarios, the equivalence of rankings of options for PROMETHEE, ELECTRE II and TOPSIS methods was found. The PROMETHEE method is also a tool used in the field of sustainable development (Ahmadi et al., 2020). The problem was the selection of parts and material suppliers within the supply chain. The existing limitations of the application of the method are highlighted and the direction of further research is indicated.

The SAW method, due to its low computational complexity, is widely used in solving decision-making problems characterised by simplicity of assumptions. As an example of use, the problem of choosing a car depending on customer preference can be pointed out (Hendrawan et al., 2020). The problem of assessing and selecting the most efficient seaport is considered in the article (Wang, 2019). The author took into account the sub-criteria concerning port services, handling, administration and fees, and indicated the possibility of modifying the calculations by using fuzzy logic.

PVM is a multi-criteria decision support method, characterised by simplicity and transparency of the algorithm and, as a result, ease of calculation. The publication (Kiseleva et al., 2020) considers the problem of choosing a route for transporting cargo from a supplier's warehouse in China to a customer located in Russia. Four shipping options were considered, which were assessed using the following criteria, i.e. cost, time, safety, reliability. The article (Kannchen et al., 2019) proposes a modification of the PVM method in order to create a ranking of investment projects in urban areas. The decision problem was that there were five options which were assessed in the following categories: spatial order, modernisation, environmental and nature protection, culture, sport and tourism. As a result of the calculations it was found that the proposed modification of the method provides a solution similar to the results obtained using AHP, TOPSIS and PROMETHEE.

Table 1 presents advantages, disadvantages and applications of multi-criteria decision support methods (Dudek et al., 2018; Wątróbski et al., 2019; Yannis et al., 2020).

The complexity of transport processes determines the need to search for new, better methods allowing for their effective optimisation (Izdebski, Jacyna-Gołda, Gołębiowski, and Plandor, 2020). Optimisation aims for identifying or finding the best (optimal) solution to a given task (optimisation problem), taking into account existing limitations. It is inherent in the optimisation, which consists of identifying the most advantageous solution, to assess the options considered. Searching for a solution to an optimisation task can be done using analytical, simulation or experimental research methods. The use of mathematical methods is possible when the description of the studied phenomena is known (the so-called mathematical model) (Izdebski, Jacyna-Gołda, Gołębiowski, Pyza, et al., 2020). It should be noted that the ratings for options awarded according to each criterion can be expressed in different units, including stimulants (maximum criteria) or destimulants (minimum criteria). Therefore, using the multi-criteria methods of assessment of options, it is necessary to carry out standardisation of the options' assessments to achieve the condition of comparability (Lewandowska et al., 2017).

In the case where the person responsible for making a decision uses not one but several selection criteria at the same time, there is a multi-criteria decision problem. This allows several partial criteria to be taken into account during the optimisation task. Examples of partial criteria used by transport service providers are (Andrzejczak and Selech, 2017; Świderski et al., 2018; Zieja et al., 2019):

– maximisation of: profit, profitability, labour productivity, fleet usage or transport work;
– minimisation of: costs, transport time, unused transport fleet.

On the other hand, the partial criteria used by the recipients of services can be (Izdebski, Jacyna-Gołda, Gołębiowski, and Plandor, 2020; Ziółkowski et al., 2019):

– maximisation of: comfort, safety, accessibility and sufficiency of the means of transport;
– minimisation of: cost and time of travel.

Table 1. Overview of multi-criteria methods in terms of disadvantages, advantages and applicability

| Method | Disadvantages | Advantages | Application |
|---|---|---|---|
| MAJA | - the impossibility of using parameters with negative values as partial criteria; | - the possibility of using multiple partial criteria expressed in different units of measurement;<br>- the possibility of implementation in decision-making problems characterised by multiple variants of solutions;<br>- possibility of visualising the solution in the form of a dominance graph;<br>- possibility of using the algorithm for both planning and decision making processes;<br>- the possibility of applying a heterogeneous set of criteria and normalising their values;<br>- the possibility of individually determining the values of weightings of the criteria and the thresholds of compliance and non-compliance according to the preference of the decision-maker; | - transport problems; |
| ELECTRE | - some versions of the method, e.g. ELECTRE III, are complicated and can be difficult for decision makers;<br>- the results obtained are not always clear to the decision-maker;<br>- the relations of superiority cause difficulties in directly identifying the strength/weakness of individual solutions;<br>- the correct determination of dominance thresholds can be a problem for the decision-maker;<br>- precise modelling of the decision-maker's preferences is time-consuming; | - ELECTRE I provides a simple analysis of the compliance indicator;<br>- the possibility of introducing additional criteria at any time during the analysis;<br>- tolerance of uncertainty and lack of precision of data;<br>- taking into account e.g. a break-even point or a veto allows to define a wide range of preferences of the decision maker;<br>- the possibility for the decision-maker to determine the weights individually; | - economics;<br>- transport problems,<br>- environment and sustainability; |
| AHP | - the need to meet the requirement for mutual independence of decision-making criteria;<br>- possible inconsistencies in the assessment and ranking criteria resulting from the pair comparison approach;<br>- possible problems arising from the interplay between criteria and alternatives;<br>- the increase in the number of criteria (variants) is reflected in an increased number of levels and hierarchical elements, which in turn results in an increase in the number of pair comparisons and thus increases the workload of the method;<br>- solving complex problems is very time consuming;<br>- critical assessments are not used, thus increasing the likelihood of errors in data conversion; | - due to its hierarchical structure, it is possible to adapt the algorithm for decision-making problems;<br>- large amount of data is not required;<br>- application to both quantitative and qualitative data;<br>- ease of implementation;<br>- comparisons between the options (criteria) allow a detailed analysis of each element of the decision problem;<br>- the possibility of checking the consistency of assessments;<br>- both definitions and structure are precisely defined; | - resource management;<br>- economics;<br>- corporate policy and strategy;<br>- process efficiency problems;<br>- planning; |

| Method | Disadvantages | Advantages | Application |
|---|---|---|---|
| TOPSIS | - requires additional information on the description of the criteria under consideration;<br>- can only be used to organise and classify a finite number of variants of the same object type;<br>- the method of weighting is not specified;<br>- the use of Euclidean distance does not take into account the correlation between the attributes; | - it allows to organise the analysed solutions on the basis of determining the shortest distance from the ideal solution and the largest from the anti-ideal solution;<br>- the simplicity of the algorithm ensures a reduction of time consumption of the calculation procedure;<br>- no need for additional conversion of the preferences of decision-makers;<br>- the simplicity of the calculation makes the algorithm easy to program;<br>- fixed number of steps, regardless of the number of attributes; | - supply chain management;<br>- business and finance;<br>- construction;<br>- environment and sustainability; |
| PROMETHEE | - the method of assigning individual weights is not specified; | - the possibility of introducing additional criteria at any time during the analysis;<br>- does not require the assumption of proportionality of the criteria;<br>- the possibility to define the preference function individually for each criterion; | - transport and logistics;<br>- economics;<br>- production processes;<br>- sustainable development; |
| SAW | - does not always reflect the actual situation;<br>- the final evaluation of the options depends on the standardisation method adopted; | - simplicity of calculations;<br>- ease of interpretation of the result obtained; | - making consumer decisions;<br>- transport and logistics; |
| PVM | - the use of Euclidean distance does not take into account the possible correlation between the criteria;<br>- the final evaluation of the options depends on the standardisation method adopted; | - simplicity of calculations and simplicity of the algorithm;<br>- a fixed number of steps regardless of the number of criteria and objects considered;<br>- the use of any scalar product makes it possible to expand the method and take into account additional factors such as uncertainty; | - transport and logistics;<br>- sustainable development; |

Thus, a transport decision problem is defined as a complex task or issue directly related to the functioning of transport systems and processes, which requires an optimal solution. The decision-making problem occurs when the decision-maker is faced with the necessity to choose the best option or make the best decision (M. Jacyna, 1998; M. Jacyna et al., 2018; Żurek et al., 2020).

This publication presents the application of the MAJA multi-criteria assessment method to solve a decision-making problem on the example of a travel means dilemma. This method has already been implemented in the decision-making processes concerning the selection of means of transport due to their technical and economic parameters (E. Sendek-Matysiak, 2019). The universal possibilities of its application in decision-making problems concerning the selection of vehicles for transport tasks were indicated (Ewelina Sendek-Matysiak and Pyza, 2018). In the publication (Pyza, 2010), the multi-criteria MAJA method was used to choose the optimal variant of transport system organization for the distribution network of products in a supply chain. Six transport solutions were analysed and the selection of the best one resulted in a 5% cost reduction. To speed up the calculations of the method's algorithm, EKSPERT computer software was used.

This article proposes an innovative area of application of the MAJA method - from the point of view of a passenger-customer who is to choose the most advantageous variant of transport on the Warsaw-Wroclaw route. The problem under consideration has not yet been researched by other authors. In addition, the disadvantages, advantages as well as examples of areas of application of multi-criteria decision support methods are listed. Moreover, a comparative analysis of the results obtained by the MAJA method was carried out in comparison with other commonly used methods. For this purpose, the considered methods were divided into domination and ranking methods. In the case of methods based on the relation of superiority, a method of determining the degree of similarity of the results through a binary matrix of the relation compatibility was proposed. The use of Spearman's linear correlation coefficient was used to examine the convergence of the received rankings.

## 2. The MAJA method

The MAJA multi-criteria assessment method consists in the selection of the best option on the basis of detailed assessments of solution options, taking into account the indicators describing the relative importance of the criteria (Leleń and Wasiak, 2019). The solution to a given optimisation task in fact boils down to the calculation of compliance and non-compliance indicators for individual assessments of criteria and the development of a dominance graph to identify the undominated option to solve the decision-making problem. It has been implemented in the problems of choosing the location of a logistics facility (Jacyna, 2008; Wei et al., 2005) and the means of transport to carry out transport tasks. The algorithm to apply the MAJA multi-criteria assessment method (Jacyna, 2006; Jacyna and Wasiak, 2015) is as follows:

1. Definition of a set of solution options $V$ and a set of partial criteria $F$, according to formulas (1) (2):

$$\boldsymbol{V} = \{\boldsymbol{v}: v = 1, \dots, N\} \quad (1)$$

$$\boldsymbol{F} = \{\boldsymbol{f}: f = 1, \dots, M\} \quad (2)$$

where:
$\boldsymbol{V}$ - a set of options;
$N$ - number of options;
$\boldsymbol{F}$ - a set of partial criteria;
$M$ - number of partial criteria.

2. Indication of the validity of partial criteria cf, assuming that the weighting of each criterion is within the range [0, 1] and the sum of the weights of all criteria takes the value 1, according to equation (3):

$$\forall \boldsymbol{f} \in \boldsymbol{F} \quad \boldsymbol{c_f} \in [\boldsymbol{0}, \boldsymbol{1}] \wedge \sum_{\boldsymbol{f} \in \boldsymbol{F}} \boldsymbol{c_f} = \boldsymbol{1} \quad (3)$$

where:
$f$ - partial criterion,
$c_f$ - importance of partial criterion $f$.

3. Formulation of a partial assessment matrix for option $X$. For each option $v \epsilon V$, this matrix establishes its partial assessment $x_{vf} \epsilon X$ in relation to each partial criterion $f \epsilon F$ (4):

$$\boldsymbol{X} = \left[\boldsymbol{x_{vf}}\right]_{\boldsymbol{N} \times \boldsymbol{M}}; \ \boldsymbol{v} \in \boldsymbol{V}, \boldsymbol{f} \in \boldsymbol{F}, \boldsymbol{x_{vf}} \in \boldsymbol{R^+} \quad (4)$$

4. Standardisation of the xvf partial assessment values of individual options to allow for comparison. The aim of standardisation is to obtain a W matrix of standardised wvf assessments of options values, according to particular criteria (5)(6):

$$\boldsymbol{w_{vf}} = \begin{cases} \dfrac{\boldsymbol{x_{vf}}}{\max\limits_{v \in V} \{\boldsymbol{x_{vf}}\}} & for\ stimulant \\ \dfrac{\min\limits_{v \in V} \{\boldsymbol{x_{vf}}\}}{\boldsymbol{x_{vf}}} & for\ destimulant \end{cases} \quad (5)$$

$$\boldsymbol{W} = \left[\boldsymbol{w_{vf}}\right]_{\boldsymbol{N} \times \boldsymbol{M}}; \boldsymbol{v} \in \boldsymbol{V}, \boldsymbol{f} \in \boldsymbol{F}, \boldsymbol{w_{vf}} \in \boldsymbol{R^+} \quad (6)$$

5. Creation of a $Z$ compliance matrix. The elements of the matrix ($z_{vv'}$ compliance indicators) are determined by comparing a pair of any two options ($v$, $v'$) while identifying those criteria $f \epsilon F$ for which option $v$ has better scores than option $v'$. The $z_{vv'}$ compliance indicator takes values from the range [0, 1]. The highest value is achieved when option $v$ achieves better marks than option $v'$ for all criteria $f \epsilon F$ (7)(8):

$$\boldsymbol{z_{vv'}} = \frac{\boldsymbol{1}}{\sum_{\boldsymbol{f} \in \boldsymbol{F}} \boldsymbol{c_f}} \sum_{\boldsymbol{f} \in \boldsymbol{F}: \boldsymbol{w_{vf}} > \boldsymbol{w_{v'f}}} \boldsymbol{c_f} \quad (7)$$

$$\boldsymbol{Z} = [\boldsymbol{z_{vv'}}]_{\boldsymbol{N} \times \boldsymbol{N}} \ ; \quad \boldsymbol{z_{vv'}} \in [\boldsymbol{0}, \boldsymbol{1}] \quad (8)$$

6. Creation of an $N$ non-compliance matrix. The value of the non-compliance index $n_{vv'}$ is the ratio of the maximum of the differences of standardised assessments when the assessment of option $v'$ was better than the assessment of option $v$, to the difference $d$ between the maximal and the minimal element of the $W$ matrix. The $n_{vv'}$ non-compliance ratio takes values from the range [0, 1]. The highest value is achieved when option $v$ achieves better marks than option $v'$ for all criteria $f \in F$ (9) (10) (11):

$$\boldsymbol{n_{vv'}} = \frac{\max\limits_{(v,f):w_{v'f}>w_{vf}} \{\boldsymbol{w_{v'f}} - \boldsymbol{w_{vf}}\}}{\boldsymbol{d}} \tag{9}$$

$$\boldsymbol{d} = \max_{(v,f)} \{\boldsymbol{w_{vf}}\} - \min_{(v,f)} \{\boldsymbol{w_{vf}}\} \tag{10}$$

$$\boldsymbol{N} = [\boldsymbol{n_{vv'}}]_{N\times N} \;; \quad \boldsymbol{n_{vv'}} \in [\boldsymbol{0}, \boldsymbol{1}] \tag{11}$$

7. Determination of the value of the $pz$ compliance threshold and the $pn$ non-compliance threshold necessary for selecting the best option $v$ from set $V$. Both thresholds must take values from the range [0; 1]. In practice, however, the compliance threshold should be in the numerical range [0,5; 1] and the non-compliance threshold in the numerical range [0; 0,5].
8. The creation of the binary domination matrix $A$. The elements of the $a_{vv'}$ dominance matrix are obtained by comparing the $z_{vv'}$ compliance indicators with the pz compliance threshold and the $n_{vv'}$ non-compliance indicators with the $pn$ compliance threshold. If $a_{vv'} = 1$, then option $v$ dominates over option $v'$ in terms of compliance and non-compliance of criteria assessments (12):

$$\boldsymbol{a_{vv'}} = \begin{cases} \boldsymbol{1} \Leftrightarrow (\boldsymbol{z_{vv'}} \geq \boldsymbol{pz} \wedge \boldsymbol{n_{vv'}} \leq \boldsymbol{pn}) \\ \boldsymbol{0} \Leftrightarrow (\boldsymbol{z_{vv'}} < pz \vee \boldsymbol{n_{vv'}} > pn) \end{cases} \tag{12}$$

9. Formulation of the $Gf$ dominance graph consisting of a set of $Wf$ vertices and a set of $Lf$ arcs (13):

$$\boldsymbol{Gf} = \langle \boldsymbol{Wf}, \boldsymbol{Lf} \rangle \tag{13}$$

where:

$Wf$ - a set of vertices that represent the analysed set of $V$ options;

$Lf$ - a set of arcs $(v, v')$, where for $a_{vv'} = 1$ there is an arc from vertex $v$ to vertex $v'$, and for $a_{vv'} = 0$ such an arc does not exist.

Selection of an undominated vertex based on the $Gf$ dominance graph. An undominated vertex is one that has only outgoing arches (or a maximum number of outgoing arches). It represents the best option $v$ from the set of viable options $V$.

Fig. 1A. and 1B. graphically shows the general algorithm of the MAJA multi-criteria assessment method.

The essence of the above presented MAJA method (Fig. 1) is to create a graph of dominance and to choose the best option. The dominance relation between each pair of analysed options depends on indicators and thresholds of compliance and non-compliance. The value of the compliance indicator is based on the adopted values of the importance of the partial criteria and the assessment of the options according to these criteria. The non-compliance indicator, on the other hand, depends on the maximum difference in the assessment of the two related options, as well as on the maximum difference in the assessment of the whole set of options of solution V. Therefore, the whole set of V influences the relations between the individual options, which means that the presence in the set of V of an option with extreme assessment values may affect the possibility of selecting the optimal option.

## 3. Results - a practical example of using the MAJA method

The optimisation task is to select the most advantageous option of meeting the needs of a passenger transport on the Warsaw-Wroclaw route. The following parameters were used as partial criteria: transport cost, travel time and travel comfort. In a given travel relation, there are different options for meeting transport needs, such as:

- rail transport: intercity, express and premium express trains;
- road transport: bus, personal car;
- air transport.

Fig. 1A. Algorithm of the MAJA multi-criteria assessment method (part A)

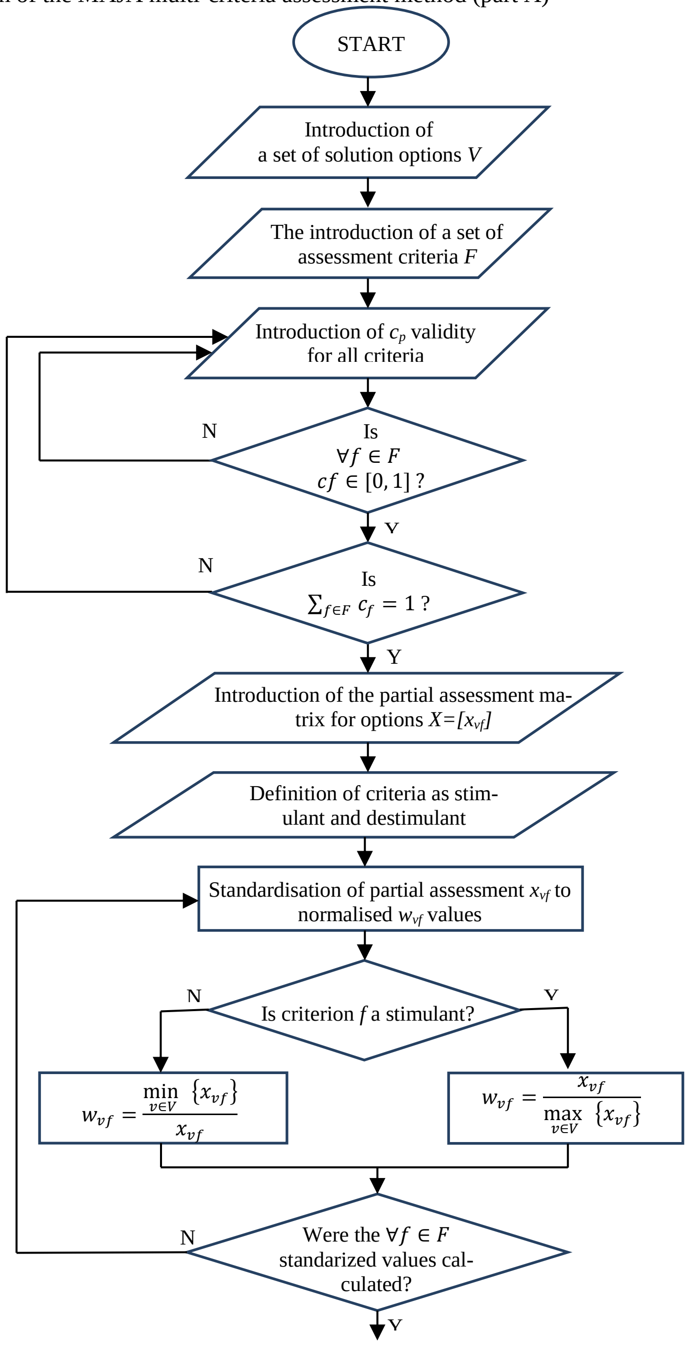
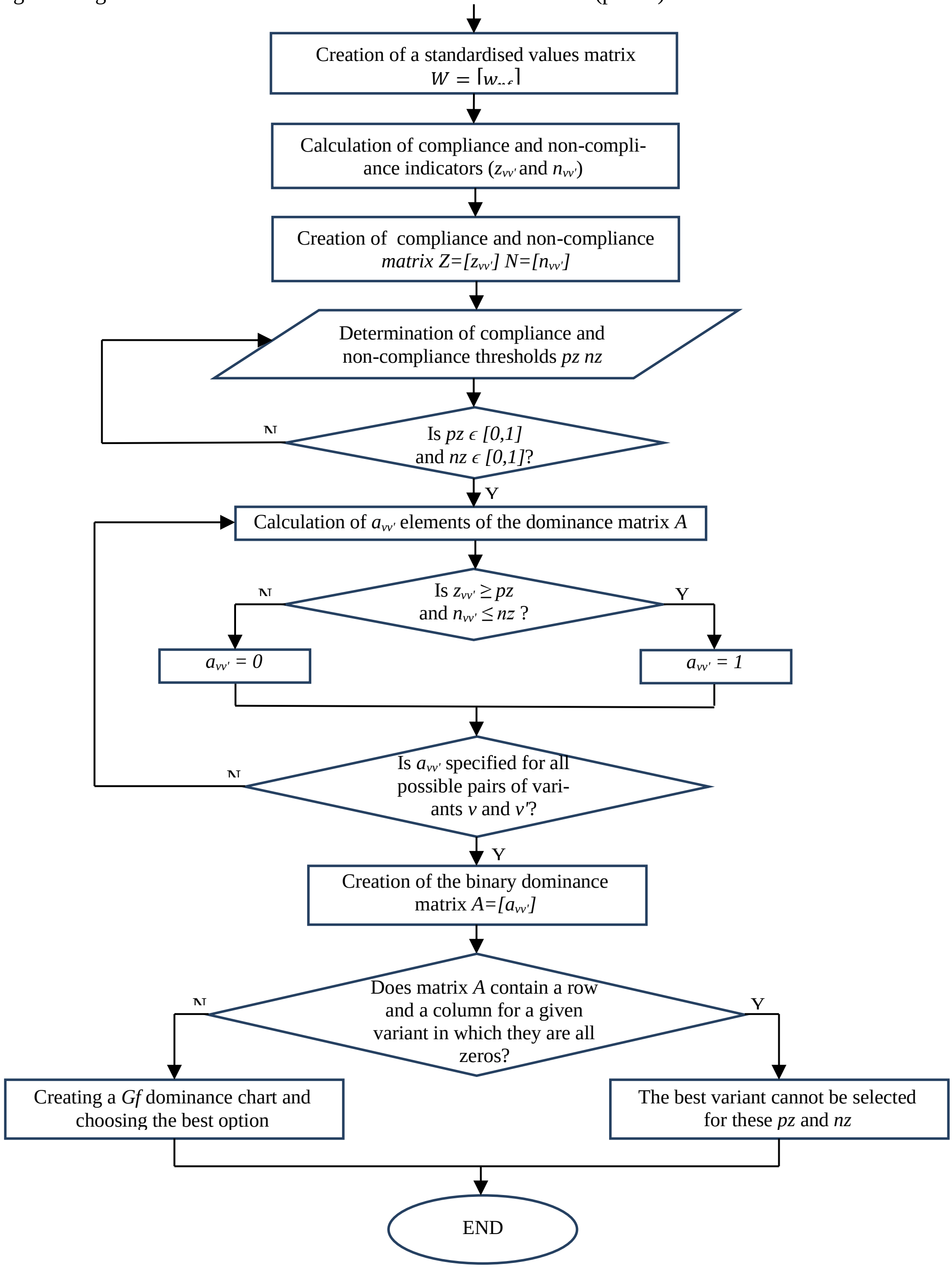


Fig. 1B. Algorithm of the MAJA multi-criteria assessment method (part B)



According to the MAJA method algorithm, a set of $V$ options (14) and a set of $F$ criteria (15) were defined:

$$V = \{v_1, v_2, v_3, v_4, v_5, v_6\} \tag{14}$$

where:
$v_1$ - intercity train,
$v_2$ - express train,
$v_3$ - premium express train,
$v_4$ - bus,
$v_5$ - car,
$v_6$ - airplane.

$$F = \{f_1, f_2, f_3\} \tag{15}$$

where:
$f_1$ - cost for 1 person. - destimulant,
$f_2$ - travel time - destimulant,
$f_3$ - travel comfort - stimulant.
On the basis of the expert assessment (Jacyna-Gołda et al., 2017), the above partial criteria have been assigned weights (importance indicators) $c_f$, which are presented in Table 2. The values of the criteria weights have been established by taking into account the mode of transport (passenger) and the distance travelled (about 350 [km]). As distance increases, travellers' preferences may put time and comfort above cost.

Table 2. The values of the criteria weights

| Criterion | $f_1$ | $f_2$ | $f_3$ | $\sum c_f$ |
|---|---|---|---|---|
| Weighting of criterion $c_f$ | 0.40 | 0.35 | 0.25 | 1.00 |

For the analysed options, an assessment matrix of these options was developed according to the adopted criteria (16). The assessment was based on the (Andrzejczak and Selech, 2017; C. Wu et al., 2015; Zieja et al., 2019):

- transportation market analysis for the cost criterion ($f_1$);
- declaration of transport service providers and navigation programme data for the travel time criterion ($f_2$);
- expert discussion for the criterion of travel comfort ($f_3$), on the scale [0 - 10].

$$X = [x_{vf}] = \begin{bmatrix} 13.45\ € & 4{:}39\ h & 4 \\ 31.15\ € & 3{:}42\ h & 7 \\ 33.62\ € & 3{:}34\ h & 9 \\ 8.97\ € & 4{:}50\ h & 2 \\ 30.03\ € & 3{:}54\ h & 7 \\ 56.03\ € & 1{:}05\ h & 8 \end{bmatrix} \tag{16}$$

The assessments were then standardised in order to ensure comparability of the assessment of the options according to the respective criteria. The normalised values are shown in the $W$ matrix (17):

$$W = [w_{vf}] = \begin{bmatrix} 0.67 & 0.23 & 0.44 \\ 0.29 & 0.29 & 0.78 \\ 0.27 & 0.30 & 1.00 \\ 1.00 & 0.22 & 0.22 \\ 0.30 & 0.28 & 0.78 \\ 0.16 & 1.00 & 0.89 \end{bmatrix} \tag{17}$$

According to the algorithm of the MAJA multi-criteria method, $Z$ (18) compliance and $N$ (19) non-compliance matrices were created:

$$Z = [z_{vv'}] \tag{18}$$

$$Z = \begin{bmatrix} 0.0 & 0.40 & 0.40 & 0.60 & 0.40 & 0.40 \\ 0.60 & 0.0 & 0.40 & 0.60 & 0.35 & 0.40 \\ 0.60 & 0.60 & 0.0 & 0.60 & 0.60 & 0.65 \\ 0.40 & 0.40 & 0.40 & 0.0 & 0.40 & 0.40 \\ 0.60 & 0.40 & 0.40 & 0.60 & 0.0 & 0.40 \\ 0.60 & 0.60 & 0.35 & 0.60 & 0.60 & 0.0 \end{bmatrix}$$

$$N = [n_{vv'}] \tag{19}$$

$$N = \begin{bmatrix} 0.0 & 0.40 & 0.69 & 0.40 & 0.40 & 0.91 \\ 0.45 & 0.0 & 0.26 & 0.85 & 0.01 & 0.84 \\ 0.48 & 0.03 & 0.0 & 0.87 & 0.04 & 0.83 \\ 0.26 & 0.66 & 0.93 & 0.0 & 0.66 & 0.93 \\ 0.44 & 0.02 & 0.26 & 0.84 & 0.0 & 0.86 \\ 0.60 & 0.15 & 0.13 & 1.00 & 0.16 & 0.0 \end{bmatrix}$$

On the basis of the rules adopted for the selection of the compliance thresholds *pz* and the non-compliance threshold *pn*, the following values of these parameters have been established (20):

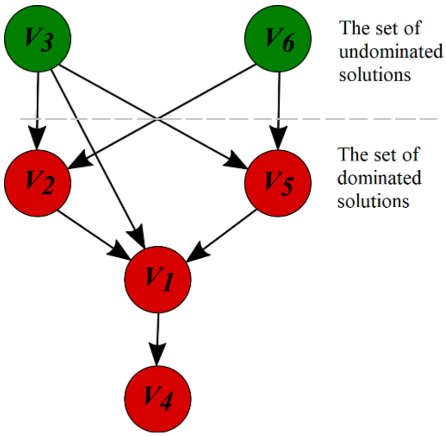
$$pz = 0.5\ pn = 0.5 \quad (20)$$

After comparing the values of $z_{vv'}$ compliance indicators with the *pz* compliance threshold and the values of $n_{vv'}$ non-compliance indicators with the *pn* non-compliance threshold, binary domination matrix *A* (21) was obtained:

$$A = [\alpha_{vv'}] = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \end{bmatrix} \quad (21)$$

The last step in the MAJA multi-criteria method is to draw a *Gf* domination graph based on the domination matrix *A*. (Figure 2).

Fig. 2. *Gf* dominance graph




Based on the *Gf* dominance graph you can determine the best option from the *V* set. According to the procedure of the MAJA multi-criteria method, the best solution is the option not dominated by the others, or the one from which the most arcs on the graph come out. Following this principle, in the example under consideration the best options are options $v_3$ and $v_6$ representing the use of premium express rail transport and airplane.

## 4. Comparison of results of other methods

Graphical visualization of the results obtained using the MAJA method and other multi-criteria decision support methods described in the introductory part of this article are summarized in Table 3. Non-dominated variants $v_3$ and $v_6$ obtained using the MAJA method have been coloured to facilitate interpretation of the solutions calculated from the other methods. Depending on the way the result is presented, the analysed decision-making methods can be divided into two groups, i.e. based on the relation of superiority and ranking methods.

The adopted division of decision-making methods determines the possibility of comparing the results obtained. Therefore, it is not possible to directly compare dominance and ranking methods. For this reason, this publication makes comparisons within the defined groups of decision-making methods, i.e. MAJA - ELECTRE I and AHP - TOPSIS - PROMETHEE - SAW - PVM.

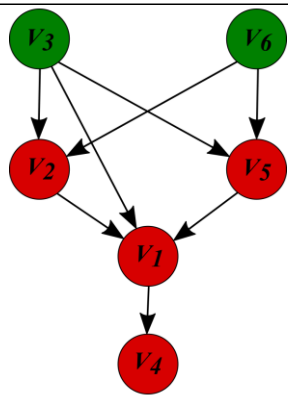
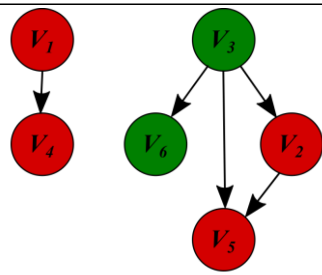
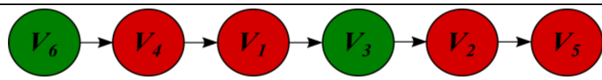
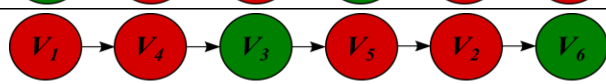
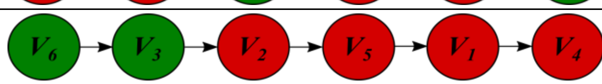
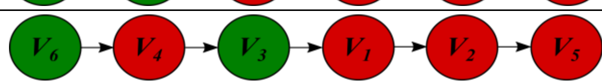
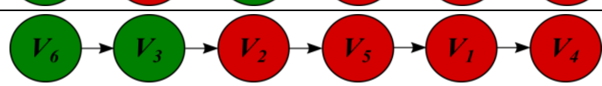
Both the MAJA and ELECTRE I methods ensured that two non-dominated and four dominated variants were identified. However, only option $v_3$ has been classified as non-dominated for both methods. In addition, the ELECTRE I method indicates option $v_1$ as non-dominated. A binary matrix *Φ* of relation of superiority between the MAJA and ELECTRE I (22) method has been constructed, in which the following determinations have been adopted:

- 1 - compliance of the compared elements of the superiority matrix,
- 0 - lack of compliance of the compared elements of the superiority matrix.

$$\Phi = \begin{bmatrix} - & 1 & 1 & 1 & 1 & 1 \\ 0 & - & 1 & 1 & 0 & 1 \\ 0 & 1 & - & 1 & 1 & 0 \\ 1 & 1 & 1 & - & 1 & 1 \\ 0 & 1 & 1 & 1 & - & 1 \\ 1 & 0 & 1 & 1 & 0 & - \end{bmatrix} \quad (22)$$

From the Φ matrix, it can be seen that in 23 comparisons of elements of the relation of superiority matrix, the results were consistent between the MAJA and ELECTRE I methods.

Table 3. Comparison of results obtained using multi-criteria methods

| Name of the method | Means of presenting the result | Final result |
|---|---|---|
| MAJA | Dominance graph |  |
| ELECTRE I | Dominance graph |  |
| AHP | Ranking of variants |  |
| TOPSIS | Ranking of variants |  |
| PROMET-HEE | Ranking of variants |  |
| SAW | Ranking of variants |  |
| PVM | Ranking of variants |  |

Only in 7 cases individual elements of the matrix did not show the correspondence of the relation of superiority. As a result, similarities can be seen in the location of the individual variants and their relationship on the domination graphs of both methods.
Table 4 shows the values of Spearman $r_{xy}$ linear correlation coefficients (23) calculated for solutions obtained by ranking methods:

$$r_{xy} = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)} \tag{23}$$

where:
$d_i$ - the difference between the ranks,
$n$ - number of variants.

Table 4. Spearman's linear correlation coefficients

| | **AHP** | **TOPSIS** | **PROMETHEE** | **SAW** | **PVM** |
|---|---|---|---|---|---|
| **AHP** | — | 0.03 | 0.09 | 0.94 | 0.09 |
| **TOPSIS** | 0.03 | — | -0.77 | -0.09 | -0.77 |
| **PROMETHEE** | 0.09 | -0.77 | — | 0.26 | 1.00 |
| **SAW** | 0.94 | -0.09 | 0.26 | — | 0.26 |
| **PVM** | 0.09 | -0.77 | 1.00 | 0.26 | — |

The highest Spearman's linear correlation coefficient equal to 1, which indicates the uniformity of the rankings, was achieved between the results obtained using the PROMETHEE - PVM methods. Moreover, a strong correlation of 0.94 has been shown for the AHP - SAW methods. In turn, a high negative correlation coefficient of -0.77 exists for the TOPSIS - PROMETHEE and the TOPSIS - PVM rankings. The remaining determined coefficients do not show correlations between other ranking pairs.

## 5. Conclusions

This publication provides a practical example of the application of the MAJA multi-criteria method in the decision making process during the choice between travel means options. The essence of the MAJA method is to determine the relationship of mutual dominance of the considered options on the basis of the adopted set of criteria, taking into account the weights and ratings assigned to these options. A graphical algorithm was developed for carrying out the assessment of options using the MAJA method, which was used in the implementation of the analysed method in decision-making problems concerning transport solutions. A practical application of the MAJA multi-criteria optimisation method is presented in the problem of choosing the optimal means of transport for travelling between two significant urban agglomerations in Poland. On the example of the Warsaw-Wroclaw route, six possible options of transport were analysed: two options for road transport, three options for rail transport and one option for air transport. In this case, the three partial criteria most relevant to the expectations of the users were analysed, i.e. cost, time and travel comfort. After the calculations were carried out, it was concluded that the best options that dominates over the other options analysed are the premium class express rail transport and airplane.

Due to the adopted classification of decision-making methods in this article, the MAJA method used was compared with the ELECTRE I method commonly used in many research fields. Both methods led to the determination of four dominated variants and two non-dominated variants, of which only variant $v_3$ was classified as non-dominated in both cases. In addition, a binary matrix of the relation of superiority compliance $\Phi$ was constructed to show the convergence of the results.

The decision problem was also solved using ranking methods such as AHP, TOPSIS, PROMETHEE, SAW, PVM. On the basis of the calculations carried out, variants $v_6$ and $v_3$ (non-dominated by the MAJA method) were placed at the first and second place in the PROMETHEE and PVM rankings. Additionally, variant $v_6$ in the AHP and SAW rankings was classified as the best. In turn, the ranking of options determined using TOPSIS differed significantly from the results obtained using the other methods.

The MAJA multi-criteria method allows for the identification of an undominated solution, which is considered optimal according to accepted criteria and assessments of solutions to the transport problem. The dominance graph graphically shows the mutual relations between the considered options. Thanks to the transparent algorithm, the presented method can be commonly used for the purposes of planning and decision-making processes. Low computational complexity, simplicity of the algorithm and calculated results convergent with other multi-criteria methods indicate the usefulness and reliability of the MAJA method in solving decision-making problems. The disadvantage of the method used is that it is not possible to use parameters with negative values as partial criteria. On the other hand, an unquestionable advantage is the possibility of applying a heterogeneous set of criteria and normalising their values. The MAJA method is recommended to aid in the problems of choosing the right type, as well as the best means of transport. The paper presents the possibilities of comparing the options of solving a decision-making problem, described by quantitative and qualitative parameters, which gives a wide spectrum of application of the described method.

A modification of the method of normalisation will be the right direction for further research, allowing for the inclusion of partial criteria with negative values for the evaluation of variants. The proposed modification will broaden the spectrum of possible uses of the method in business and finance. An example of such an application is the problem of assessing companies taking into account profit from their activities, interpreted as a decision criterion which, if a loss is achieved, takes a negative value. Financial decision making is always fraught with uncertainty, which justifies the use of tools to describe the rules governing the financial market, which include stochastic dominance. In the opinion of the authors of this publication, it is reasonable to address the issues related to the indication of relations between the MAJA method and stochastic dominations, which will be the subject of the next publication.

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# PROSPECTS FOR THE DEVELOPMENT OF ELECTRIC VEHICLE CHARGING INFRASTRUCTURE IN POLAND IN THE LIGHT OF THE REGULATIONS IN FORCE

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## *Abstract:*

*The Polish electric mobility market, presently at a relatively early development stage, cannot compete with traditional means of transport in relation to the number of locations enabling drivers to "refuel" their vehicles. Simultaneously, extension of the network of publicly available EV charging stations constitutes a vital prerequisite for electric vehicle industry development. The feeling of range anxiety connected with limited access to suitable EV charging outlets, in particular during longer trips, discourages potential buyers from purchasing electric vehicles, and, as a result, limited demand hinders development of this industry. In January 2018, the Polish Parliament (the Sejm) passed the Act on electromobility and alternative fuels which establishes a certain system and provides a number of objectives vital for electric vehicle market development. Being aware of the fact that, at least for the first few years, infrastructure development is a key factor, the legislator, in Art. 60, section 1 of the Act, establishes a minimum number of EV charging outlets to be installed in Polish communes, by 31 December 2020. However, no detailed guidelines as to their location were given. It only indicates a minimum number of them, which should be established in communes with a given demographic and transport characteristics of the commune ie the number of inhabitants and motor vehicles and the number of cars per 1000 inhabitants of the commune. The purpose of this article is to indicate in which, specifically, municipalities, according to the act, electric vehicles charging outlets are to be located. Based on the analysis performed it was determined that publicly available EV charging outlets must be installed only in 32 of 2477 communes in Poland and and these are municipalities. Identification of such communes made it possible to determine the distances between them, which made it possible to verify whether the network of EV charging infrastructure planned on the basis of the guidelines in the Act will enable efficient route travel in the future without experiencing any range anxiety. In addition, the existing market conditions were presented and discussed, with an indication of whether they are conducive to meeting the minimum set in the Act regarding the number of charging points. The conducted analysis is an introduction to further research on determining the optimal distribution of charging outlet in Poland.*

**Keywords:** *electromobility, EV charging outlet, infrastructure, EV charging station, electric vehicle*

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## 1. Introduction

The acceleration of civilisational development observed since the end of the 18th century, in addition to a number of achievements, has resulted in gradual depletion of natural resources, impoverishment of the biosphere, ecological imbalance as well as lot of destruction, disasters and threats (Hiwaki, K., 2019; Khvatova, M.A., Magomedov, R.M., and Magomedrasulov. M.N. et al., 2019; Kochneva, L.V., Kurakin, A.V., and Be-Lov, V.E. et al., 2019; Ledwith, M., 2020; Sztumski, W., 2019). Thus the previous assumption stating that social development stems from the drive to satisfy people's material needs has been revised and rendered as incomplete (Jodkowska, L., 2001). The necessity to take into account the role of social and environmental factors, in addition to the economic dimension, in economic activity, with a view to satisfying the needs not only of the current generation but also the future ones, in line with the concept of sustainable development, has started being recognised (Fig. 1).

The European Union has been promoting the sustainable development concept for many years now. In particular, this refers to the transport sector which, among various anthropology divisions, is responsible for over a quarter of greenhouse gas (GHG) emissions, which makes it the second largest source of such emissions (Fig. 2) (COM, 2016).

The Community's objective is to create such an organised transport system that will adhere to the sustainable development rules, i.e. a system making transport and mobility services available to all inhabitants in a safe and environmentally-friendly manner, this contributing to economic development and society's prosperity enhancement (Correa, D.F., Beyer, H.L., Fargionec, J.E. et al., 2019; Nikołajewka, A., Adey, P., Cresswell, T. et al., 2019; Pisonia, E., Christidis, P., Thunis, P., and Trombetti, M., 2019; Standing, C., Standing, S., and Biermann, S., 2019; Zhao, X., Ke, Y., and Zuo, J. et al., 2020). Despite the fact that a sustainable transport system should integrate various modes of transport, taking into account the fact that road transport, in particular passenger vehicles (Fig. 3) whose numbers still increase in the European Union (Fig. 4), is responsible for most emissions (i.e. 73%), this sector requires altering the mobility paradigm, in the short-time perspective.

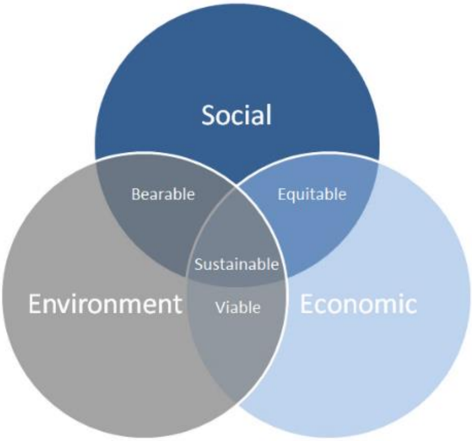


Fig. 1. Three pillars of sustainable development

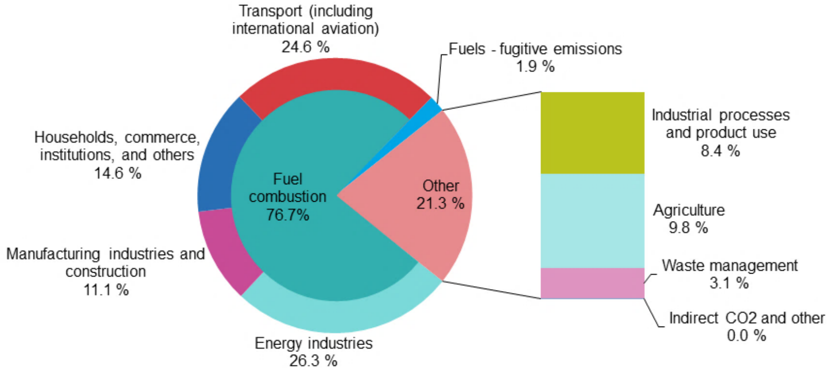


Fig. 2. Greenhouse gas emissions by IPCC (The Intergovernmental Panel on Climate Change) source sector, EU-28, 2017 (ESE, 2017)

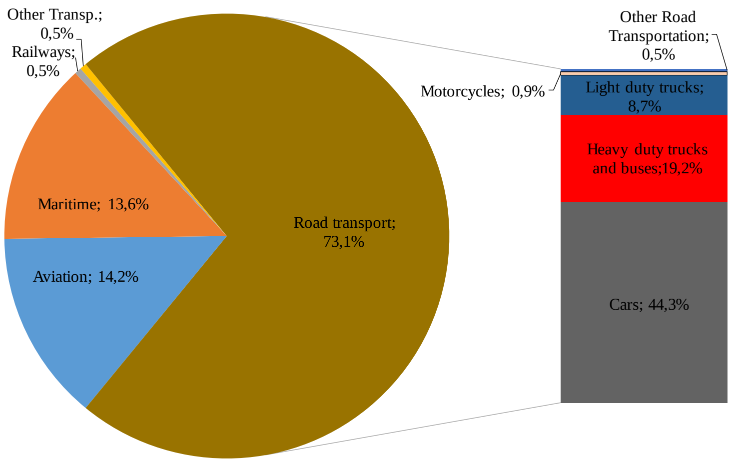


Fig. 3 Greenhouse gas emissions in the European Union transport sector, in 2017 (proprietary compilation based on (EUROSTAT))

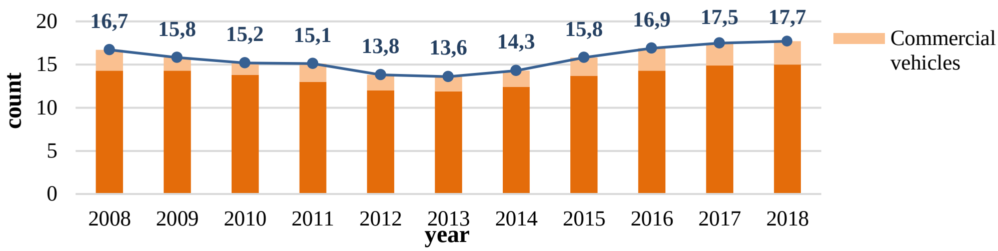


Fig. 4. Sales of vehicles in the European Union (million) (proprietary compilation based on (EAMA))

The method for bringing about this transformation is defined in the strategy developed in the White Paper, i.e. “Roadmap to a Single European Transport Area-Towards a competitive and resource efficient transport system” applicable in the European Union. The strategy encompasses ten extremely ambitious objectives simultaneously constituting guidelines for future actions and means for measuring development in the process of ensuring low-emission and zero-emission transport. The objectives include the goal of halving the use of conventionally-fuelled cars in urban transport by 2030, and phasing them out in cities by 2050 (EUWP, 2011).

Electromobility is a serious alternative for conventional mobility systems which has been gaining in popularity in the entire EU area (Milojević, S., Skrucany, T.H., and Stanojević, D. et al., 2018).

In 2011-2018, the number of new ECVs (Electric Commercial Vehicles) increased by 84% on average, on the year-to-year basis (Table 1).

In 2018, electrically-chargeable vehicles accounted for 2.0% of new cars registered across the EU, which is demonstrated in Figure 5. Such development is expected to continue over the next several years with special subsidy packages, as addressed in references (Babić, D., Bajor, I., and Babić, M.I., 2010; Hoerstebrock, T., Hahn, and A., Sauer, J., 2014), and especially in reference (Carbon, C.C., and Gebauer, F., 2017).

## 2. Current electromobility status in Poland

In Poland, the general acceptance of electricity-fuelled vehicles is much less significant. The share of such vehicles in the total number of vehicles on the automotive market registered in 2019 was only - 0.5% (Fig. 6). In that period, 8637 passenger electric vehicles were registered, including 5091 (i.e. 59%) Battery Electric Vehicles (BEV) and 3546 Plug-in Hybrid Electric Vehicles (PEHV).

Table 1. Number of electric vehicles in the European Union, in 2011-2019 (growth, dynamics) (proprietary compilation based on (EAFO))

| Year | Number of ECVs registrations | Absolute increase (in relation to the previous year) | Growth rate in % |
|---|---|---|---|
| 2011 | 35 | - | - |
| 2012 | 66 | 31 | 89% |
| 2013 | 103 | 37 | 56% |
| 2014 | 257 | 154 | 150% |
| 2015 | 489 | 232 | 90% |
| 2016 | 773 | 284 | 58% |
| 2017 | 1712 | 939 | 121% |
| 2018 | 3079 | 1367 | 80% |
| 2019 | 4688 | 1609 | 52% |
| average change rate | | 1.84 | |
| medium-term change rate | | 84% | |

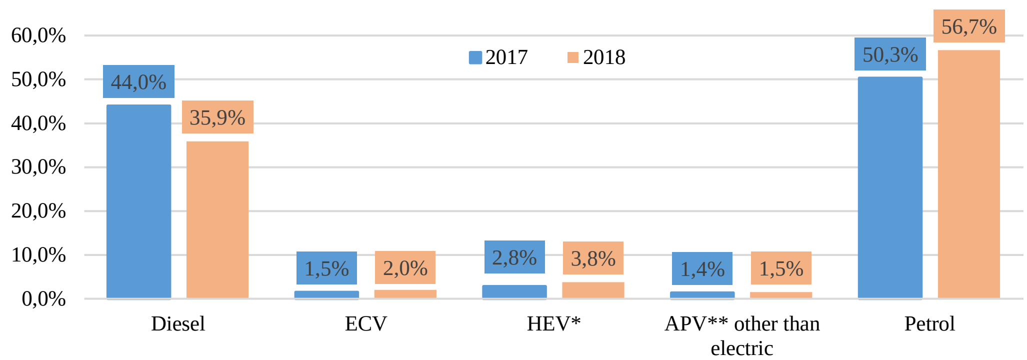


Fig. 5. New passenger cars in the EU by fuel type, % share (proprietary compilation based on (EAMA))

The negligible number of currently operated electric vehicles shows that the electric mobility market in Poland is still in its initial development phase. According results of research conducted among Polish drivers, the reason for marginal interest in ECVs is mostly their high prices and technical constraints, e.g. lack of sufficiently developed, publicly available charging infrastructure (Table 2), despite the fact that approx. 70 - 80% electric vehicle charging operations are performed in domestic facilities, and the average route (approx. 23 km, according to the Motor Transport Institute) can be driven without recharging. Also, recent literature has investigated the variety of barriers that EVs face, and generally found that typical barriers include range, and charging infrastructure (Krawiec, S., and Krawiec, K., 2017; Sendek-Matysiak, E., and Szumska, E., 2018; Wierzbowski. P., 2019; Zaniewska-Zielińska, D., 2018; Sendek-Matysiak, E., 2020). In (Sovacool, B.K, and Hirsh, R.F., 2009), implementing a qualitative literature review, found that EVs faced a variety of barriers, including price, conflicting social and cultural values, and charging infrastructure. Secondly many transport economists have attempted to quantify the barriers in choice experiments, typically finding that price, range, and charging infrastructure/time are the most costly barriers (Hidrue, M.K., Parsons, G.R., Kempton, W., and Gardner. M.P., 2011; Schuitema, G, Anable, J, Skippon, S, and Kinnear, N., 2013). Other more recent literature have also consistently found similar yet varied barriers. For example, in (Graham-Rowe, E., Gardner, B., Abraham, C.,) utilizing test drives and interviews, found that range, price, aesthetics and symbolic value were the primary barriers to EV adoption.

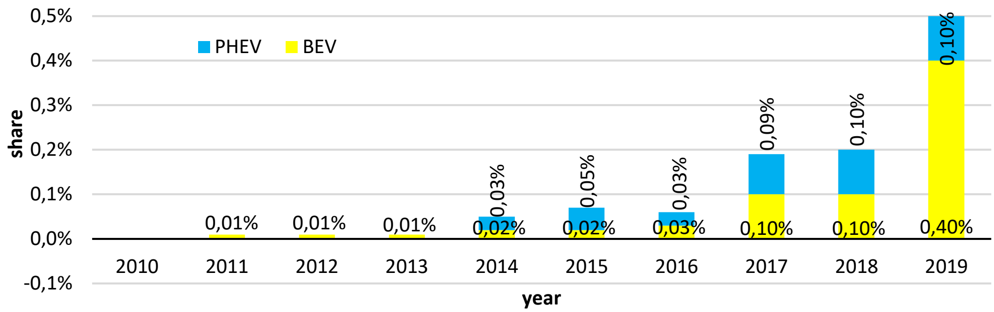


Fig. 6. Share of electric vehicles in the total number of new AF type vehicles registered in Poland (proprietary compilation based on (EAFO))

Finally, in (Rezvani, Z, Jansson, J, and Bodin, J., 2015) an extensive literature review was carried out and it was found that price, range, charging infrastructure, and consumer perceptions and knowledge to be central and consistent barriers, among various others. Thus, range and range anxiety is a prominent fixture in the literature as one of the more substantial barriers to EV adoption. A litany of studies articulate how range poses a barrier to EV adoption, firstly by investigating the technical requirements of an EV (Pearre, N.S, Kempton, W., Guensler, R.L, and Elango, V.V., 2011), or based on the psychology and inexperience of the consumer (Franke, T., and Krems, J.F., 2013). Curiously, however, the understanding of range anxiety is still nebulous, especially as it continues to persist as a barrier despite the increasing range of EVs, the development of public charging infrastructure, and more consumer education and experience.

According to (CROV; PAFA; PAIA), in 2019, there were 1011 EV charging stations available in Poland (1815 publicly available charging outlets, including 28% of direct current (DC) chargers).

In that period, one publicly available EV charging outlet was provided per 5 electric vehicles (in line with Directive 2014/94/EU of the European Parliament and of the Council, i.e. “Clean Power for Transport”, it is recommended that, by 2020, in Member States, there should be one publicly available EV charging outlet per 10 registered vehicles of this type (PAFA)) (Fig. 7).

Table 2. Answers to the “What, in your opinion, are the largest barriers for electric vehicle development in Poland?” question given by respondents surveyed

| Source | Poorly developed EV charging station infrastructure (%) |
|---|---|
| (EMP) | 48.0 |
| (PAFA) | 47.4 |
| (INNOGY) | 41.0 |
| (KPMG) | 21.0 |

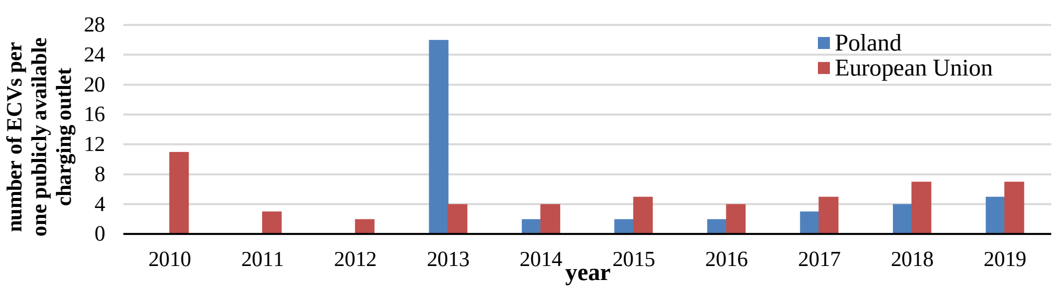


Fig. 7. Number of electric vehicles per one publicly accessible EV charging outlet (proprietary compilation based on (EAFO))

However, this indicator does not reflect the correct level of the EV charging infrastructure development in Poland. Apart from the quantitative value, a network of EV chargers should also be characterised by their optimum distribution in a given country. A network of EV charging stations must facilitate efficient driving within a given route, without experiencing the range anxiety resulting from the fear that a vehicle may run out of charge within a given section of the route, failing to reach its destination (JAKOBSSON, N., GNANN, T., PLÖTZ, P. et al., 2016). Thus a parameter more effectively demonstrating the EV charging infrastructure development condition is the density of charger distribution. In Poland, there are 3 EV charging stations per 1000 km$^2$. In comparison, there are 990 charging stations per the same area in the Netherlands, which are the leader among all European countries within this scope (Fig. 8).

Figure 9 shows that, in Poland, EV charging stations are located mostly in large cities (48% (Fig. 10)) and along main traffic routes. This is one of the factors contributing to the fact that, presently, the electromobility development in Poland is limited mostly to largest cities.

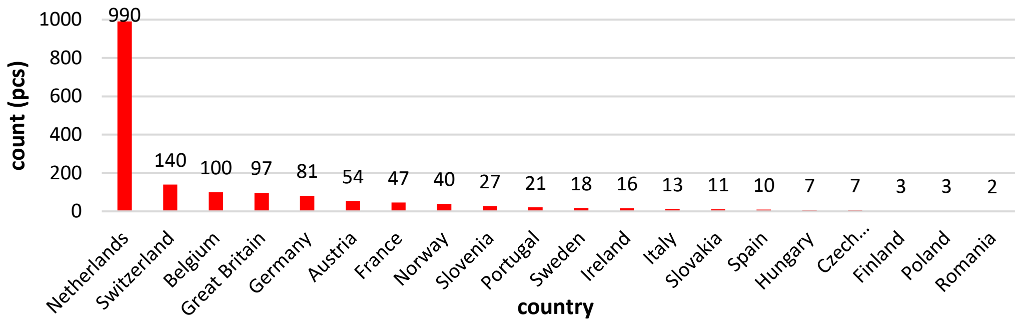


Fig. 8. Number of publicly available EV charging stations per 1000 km$^2$ in European countries (proprietary compilation based on (EAFO))

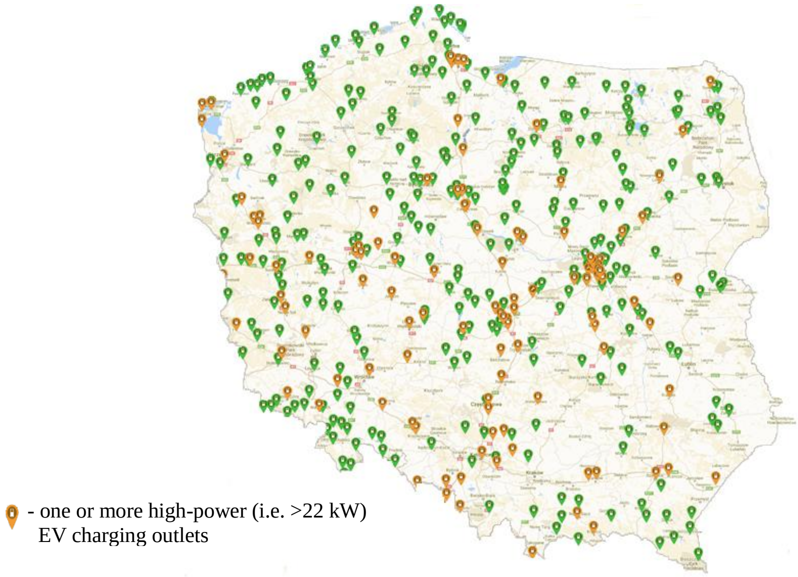


Fig. 9. Distribution of EV charging stations in Poland, in 2020 (as of March 2020) (PSEV)

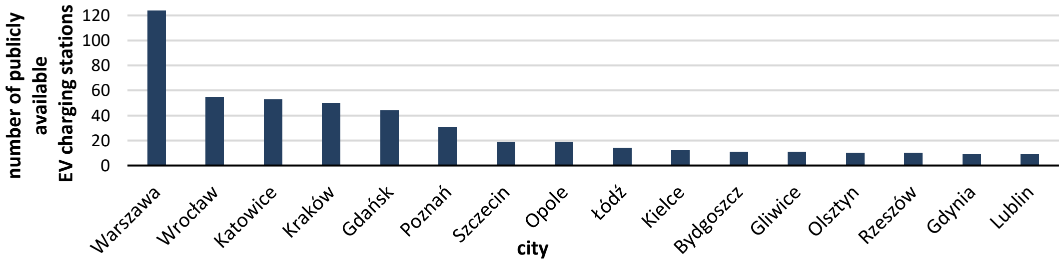


Fig. 10. Cities where most EV charging stations were located in 2019 (pieces) (own compilation based on (CROV; PAFA; PAIA))

## 3. EV charging infrastructure development forecasts

A correctly developed and functioning network of EV charging outlets is a factor necessary to exert impact on consumers' preferences and dispel their fears connected with driving vehicles fuelled with alternative power sources. Due to the above, in January 2018, the Polish Parliament passed the Act on electromobility and alternative fuels, in which Art. 60 obliges local governments to commission a necessary EV charging infrastructure, by 31 March 2021 (ELECTROMOBILITY, 2018). The Act defines the minimum number of EV charging outlets in publicly available charging stations, on the basis of demographic and transport characteristics of a given commune (Table 3).

While using the Central Statistical Office data for 2018 regarding the number of inhabitants and motor vehicles and referring the guidelines provided in the above-mentioned Act, it was determined that publicly available EV charging outlets must be installed only in 32 of 2477 communes in Poland. All communes where publicly available EV charging stations must be provided are urban communes (Table 4) where the number of inhabitants is at least 100,975. Taking into account the 32 communes where, according to the Act, EV chargers must be installed, there is only one commune where the minimum number of such chargers should be 1000 (as for the remaining communes - 210 chargers in 6 communes, 100 chargers in 13 communes and 60 chargers in 12 communes). According to the legislator, there must be at least 4280 new publicly available EV charging outlets provided, in total. See Table 5 for the list of communes and the minimum number of EV charging outlets to be installed.

When identifying communes in which, according to the Act, the minimum number of charging outlets is to be launched, their density in the area of a given commune was determined according to the formula (1).

$$charging\ outlets\ density = \\ = \frac{number\ of\ EV\ charging\ outlets\ (pcs)}{area\ if\ the\ communes\ (km2)} \quad (1)$$

The area of communes, the minimum number of EV charging outlets, as well as the number of EV charging outlets per 1 km$^2$ are presented in Table 6. Then, based on the road distance between the seats of these communes, the distances between them were determined (Fig. 12).

Figure 11 presents distances between neighbouring communes where, in line with the Act of 11 January 2018 on electromobility and alternative fuels, the minimum number of publicly available EV charging outlets is to be commissioned.

The largest distance between such communes is 359 km (Gdańsk-Szczecin), and the smallest distance is 10 km (Gliwice – Zabrze).

Table 3. Minimum number of charging outlets in publicly available charging stations in Poland (by 31 March 2021) (proprietary compilation based on (ELECTROMOBILITY, 2018))

| Population | Number of mot. vehicles | Number of mot. vehicles per 1000 inhabitants | Number of charging outlets |
|---|---|---|---|
| >1,000,000 | ≥ 600,000 | ≥ 700 | 1000 |
| > 300,000 | ≥ 200,000 | ≥ 500 | 210 |
| > 150,000 | ≥ 95,000 | ≥ 400 | 100 |
| > 100,000 | ≥ 60,000 | ≥ 400 | 60 |

Table 4. Number of communes broken down in terms of Voivodeships and number of communes where publicly available EV charging outlets must be installed, in line with the provisions of the Act of 11 January 2018 on electromobility and alternative fuels (proprietary compilation based on (ELECTROMOBILITY, 2018; CSO))

| Item | Territorial division unit | | | | Count | | | |
|---|---|---|---|---|---|---|---|---|
| | communes | | | | communes where publicly available EV charging outlets must be installed | | | |
| | urban | rural | urban-rural | total | urban | rural | urban-rural | total |
| Poland | 302 | 1533 | 642 | 2477 | 32 | - | - | 32 |
| Lower Silesian Voivodeship | 35 | 78 | 56 | 169 | 1 | - | - | 1 |
| Kuyavian-Pomeranian Voivodeship | 17 | 92 | 35 | 144 | 2 | - | - | 2 |
| Lublin Voivodeship | 20 | 165 | 28 | 213 | 1 | - | - | 1 |
| LubuszVoivodeship | 9 | 39 | 34 | 82 | 2 | - | - | 2 |
| ŁódźVoivodeship | 18 | 131 | 28 | 177 | 1 | - | - | 1 |
| Lesser Poland Voivodeship | 14 | 120 | 48 | 182 | 1 | - | - | 1 |
| Masovian Voivodeship | 35 | 225 | 54 | 314 | 3 | - | - | 3 |
| Opole Voivodeship | 3 | 35 | 33 | 71 | 1 | - | - | 1 |
| SubcarpathianVoivodeship | 16 | 109 | 35 | 160 | 1 | - | - | 1 |
| PodlaskieVoivodeship | 13 | 78 | 27 | 118 | 1 | - | - | 1 |
| Pomeranian Voivodeship | 22 | 81 | 20 | 123 | 2 | - | - | 2 |
| Silesian Voivodeship | 49 | 96 | 22 | 167 | 11 | - | - | 11 |
| Holy Cross Voivodeship | 5 | 58 | 39 | 102 | 1 | - | - | 1 |
| Warmian-MasurianVoivodeship | 16 | 66 | 34 | 116 | 1 | - | - | 1 |
| Greater Poland Voivodeship | 19 | 113 | 94 | 226 | 2 | - | - | 2 |
| Western Pomeranian Voivodeship | 11 | 47 | 55 | 113 | 1 | - | - | 1 |

Table 5. Minimum number of publicly available EV charging outlets, in line with the provisions of the Act of 11 January 2018 on electromobility and alternative fuels (proprietary compilation based on (ELECTROMOBILITY, 2018; CSO))

| Voivodeship | Commune | Count | Voivodeship | Commune | Count |
|---|---|---|---|---|---|
| Lower Silesian Voivodeship | Wrocław | 210 | Silesian Voivodeship | Bielsko-Biała | 100 |
| Kuyavian-Pomeranian Voivodeship | Bydgoszcz | 100 | | Bytom | 60 |
| | Toruń | 100 | | Częstochowa | 100 |
| Lublin Voivodeship | Lublin | 100 | | DąbrowaGórnicza | 60 |
| LubuszVoivodeship | Gorzów Wielko- | 60 | | Gliwice | 100 |
| | ZielonaGóra | 60 | | Katowice | 100 |
| ŁódźVoivodeship | Łódź | 210 | | RudaŚląska | 60 |
| Lesser Poland Voivodeship | Krakow | 210 | | Rybnik | 60 |
| Masovian Voivodeship | Płock | 60 | | Sosnowiec | 100 |
| | Radom | 100 | | Tychy | 60 |
| | Warsaw | 1000 | | Zabrze | 60 |
| Opole Voivodeship | Opole | 60 | Warmian-MasurianVoivodeship | Olsztyn | 60 |
| SubcarpathianVoivodeship | Rzeszów | 100 | Greater Poland Voivodeship | Kalisz | 60 |
| PodlaskieVoivodeship | Białystok | 100 | | Poznań | 210 |
| Pomeranian Voivodeship | Gdańsk | 210 | | | |
| | Gdynia | 100 | Western Pomeranian Voivodeship | Szczecin | 210 |
| Holy Cross Voivodeship | Kielce | 100 | | | |

Table 6. Minimum number of EV charging outlets in Poland per 1 km$^2$, in line with the provisions of the Act of 11 January 2018 on electromobility and alternative fuels (proprietary compilation based on (ELECTROMOBILITY, 2018; CSO))

| Commune | Area (km$^2$) | Count | Number of charging outlets per 1 km$^2$ | Commune | Area (km$^2$) | Count | Number of charging outlets per 1 km$^2$ |
|---|---|---|---|---|---|---|---|
| Wrocław | 292.8 | 210 | 0.72 | Bielsko-Biała | 124.5 | 100 | 0.80 |
| Bydgoszcz | 176 | 100 | 0.57 | Bytom | 69.44 | 60 | 0.86 |
| Toruń | 115.7 | 100 | 0.86 | Częstochowa | 160 | 100 | 0.63 |
| Lublin | 147 | 100 | 0.68 | DąbrowaGórnicza | 189 | 60 | 0.32 |
| Gorzów | 86 | 60 | 0.70 | Gliwice | 134.2 | 100 | 0.75 |
| ZielonaGóra | 278.3 | 60 | 0.22 | Katowice | 164.7 | 100 | 0.61 |
| Łódź | 296.2 | 210 | 0.71 | RudaŚląska | 77.73 | 60 | 0.77 |
| Krakow | 327 | 210 | 0.64 | Rybnik | 148.4 | 60 | 0.40 |
| Płock | 88.06 | 60 | 0.68 | Sosnowiec | 91.06 | 100 | 1.10 |
| Radom | 111.8 | 100 | 0.89 | Tychy | 81.81 | 60 | 0.73 |
| Warsaw | 517.2 | 1000 | 1.93 | Zabrze | 80.4 | 60 | 0.75 |
| Opole | 149 | 60 | 0.40 | Olsztyn | 88.33 | 60 | 0.68 |
| Rzeszów | 126.6 | 100 | 0.79 | Kalisz | 69.41 | 60 | 0.86 |
| Białystok | 102.1 | 100 | 0.98 | Poznań | 261.8 | 210 | 0.80 |
| Gdańsk | 262 | 210 | 0.80 | | | | |
| Gdynia | 135.1 | 100 | 0.74 | Szczecin | 300.6 | 210 | 0.70 |
| Kielce | 109.4 | 100 | 0.91 | | | | |

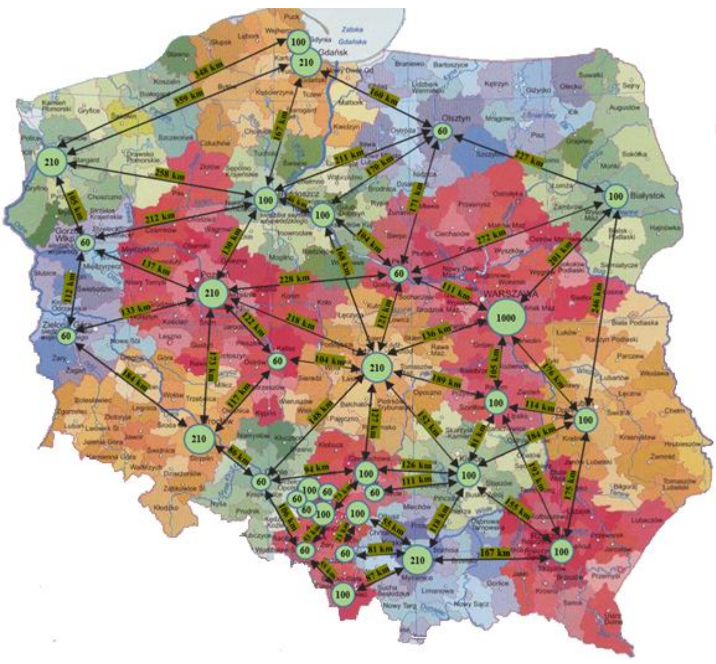

Fig. 11. Minimum number of publicly available EV charging outlets and distances between communes where the outlets should be commissioned (proprietary compilation based on (ELECTROMOBILITY, 2018; CSO)

According to the legislator, the number of charging outlets installed in publicly available EV charging stations mentioned in section 1 includes the charging outlets located along the Trans-European Transport Network (TEN-T) (ELECTROMOBILITY, 2018).
In September 2018, the General Directorate for National Roads and Motorways published the plan of publicly available EV charging station locations at Passenger Service Points within the basic TEN-T network. According to the submitted plan, from 31 March 2021, EV charging stations will be installed at 159 Passenger Service Points, along public national roads of class A and S, i.e. along motorways and expressways (Table 7).
See Figure 12 for the locations where EV charging stations should be commissioned, in line with the Act on electromobility and alternative fuels. EV charging station locations situated along the TEN-T network routes are marked green.

## 4. Conditions and implementation possibilities

Taking into account the existing EV charging infrastructure and provisions of the Act of 11 January 2018 on electromobility and alternative fuels, in March 2021, in Poland, there should be 4280 publicly available EV charging outlets in operation (according to (POOOIAT), in 2019, there were 7807 petrol stations in Poland), which means that their number should increase by 250% in relation to the number of outlets available in 2019.
In order to achieve the minimum number defined in the Act, in this year, the largest number of EV chargers must be commissioned in Radom. There, their number must increase by 1050%. On the other hand, the number of publicly available EV charging outlets in Katowice must increase by only 2% as compared to 2019, which is the smallest number of outlets necessary to be commissioned.

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Table 7. Planned number of EV charging stations located along TEN-T network routes in Poland (proprietary compilation based on (GDFNR; GM; TARGEO))

| Road class | Road no. | Direction | Length of road section where an EV charging station is to be built (km) | Number of EV charging stations | Distance between consecutive EV charging outlets (km) | | | Direction | Length of road section where an EV charging station is to be built (km) | Number of EV charging stations | Distance between consecutive EV charging outlets (km) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | avg. | min. | max. | | | | avg. | min. | max. |
| motorway | 1 | Gorzyczki | 555.60 | 19 | 19.59 | 7.95 | 35.70 | Gdańsk | 532.95 | 20 | 19.76 | 7.95 | 37.70 |
| motorway | 2 | Kukuryki | 531.55 | 16 | 35.44 | 10.08 | 128.50 | Świecko | 532.30 | 16 | 35.49 | 10.08 | 128.30 |
| motorway | 4 | Korczowa | 639.00 | 22 | 30.43 | 14.84 | 140.05 | Jędrzychowice | 636.15 | 22 | 30.29 | 14.39 | 140.40 |
| motorway | 6 | Szczecin | 25.7 | 1 | - | - | - | Berlin | 25.70 | 1 | - | - | - |
| expressway | 3 | Lubawka | 144.10 | 5 | 36.03 | 16.40 | 46.80 | Szczecin | 163.70 | 5 | 40.93 | 19.60 | 52.80 |
| expressway | 61 | Ostrów Mazowiecki | 39.50 | - | - | - | - | Suwałki | 39.50 | 1 | - | - | - |
| expressway | 7 | Warsaw | | 4 | 31.33 | 24.00 | 40.00 | Gdańsk | | 7 | 51.47 | 64.17 | 313.58 |
| expressway | 8 | Wrocław | 429.65 | 8 | 48.93 | 6.11 | 264.00 | Białystok | 440.40 | 10 | 61.38 | 11.80 | 267.61 |
| expressway | 19 | Rzeszów | 20.76 | 1 | - | - | - | Lublin | 20.76 | 1 | - | - | - |

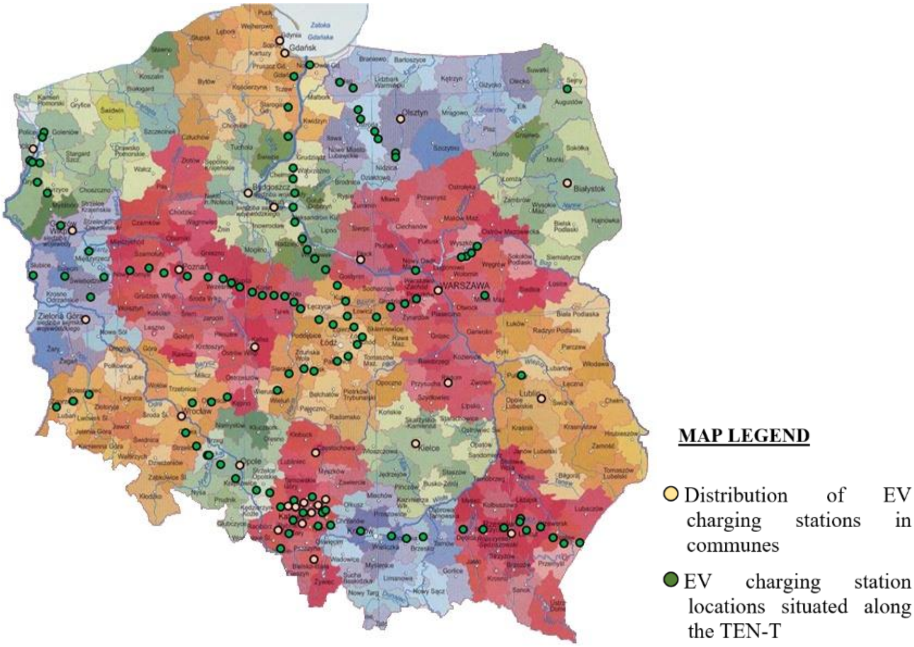


Fig. 12. Locations of EV charging outlets in Poland, in line with the provisions of the Act of 11 January 2018 on electromobility and alternative fuels (proprietary compilation based on (ELECTROMOBILITY, 2018; CSO; GDFNR))

In order to achieve the minimum number defined in the Act, in this year, the largest number of EV chargers must be commissioned in Radom. There, their number must increase by 1050%. On the other hand, the number of publicly available EV charging outlets in Katowice must increase by only 2% as compared to 2019, which is the smallest number of outlets necessary to be commissioned.

See Table 8 for the number of publicly available EV charging outlets, i.e. currently operational and recommended in the Act.

Taking into account the existing market conditions, achieving the minimum number of chargers, as assumed in the Act on electromobility and alternative fuels, in all cities is highly unlikely. The city of Katowice is an exception, as there are already 98 operational publicly available EV charging outlets and, in line with the Act, their number must be at least 100, in March 2021. It results from several premises. Presently, construction of an EV charging station is a costly, time-consuming and complex undertaking. Moreover, it requires concluding certain agreements and obtaining numerous permits. In case connection to the existing distribution network is planned, it is necessary to conclude a connection agreement, the implementation of which often involves a number of issues, i.e. lack of property owners' consent to enter the premises, process of obtaining necessary administrative permits that may last for as long as 18 months, restrictions on network expansion possibilities (e.g. within road lanes, which results from the provisions of the Act on roads) or lack of regulations facilitating acquisition of the right-of-way for new lines (no Act on transmission corridors).

Additionally, there is another formal barrier which hinders the EV charging station construction process, i.e. a problem with obtaining data concerning the power of existing connections a given station might potentially belong to. Such data is necessary to connect chargers to existing power networks. The process of obtaining necessary information regarding construction of an EV charging station is often time-consuming or even impossible to complete. Moreover, entities interested in constructing an EV charging station claim that distribution network operators treat the connection process in a fairly “straightforward” manner, i.e. in case connection conditions are not present (e.g. due to insufficient network infrastructure in a given area), they simply refuse to connect a station, without specifying any possible alternative locations. This has particularly negative impact on car dealership networks and their service points which should be able to charge electric vehicles subject to servicing. (KPGM; PAIA; SSW, 2019).

Presently, in numerous cases, an investment project consisting in constructing an EV charging station is simply economically unjustified. The costs borne in relation to maintaining a station are disproportionate to revenues resulting from charging the still meagre numbers of electric vehicles in Poland. Agreements specifying a volume of energy that must be purchased are another issue to be faced by EV charger operators, as such energy is not always fully used by the users. Moreover, the presently applicable distribution tariffs in Poland are incompatible with market needs.

Table 8. Number of publicly available EV charging outlets in Poland (state for March 2020 and according to (ELECTROMOBILITY, 2018)

| **Voivodeship** | **Commune** | **Number of publicly available EV charging outlets** | | **Increase (%)** |
|---|---|---|---|---|
| | | **March 2020** | **ELECTROMOBILITY** | |
| Lower Silesian Voivodeship | Wrocław | 93 | 210 | 126 |
| Kuyavian-Pomeranian Voivodeship | Bydgoszcz | 29 | 100 | 245 |
| | Toruń | 22 | 100 | 355 |
| Lublin Voivodeship | Lublin | 26 | 100 | 285 |
| LubuszVoivodeship | Gorzów Wielkopolski | 13 | 60 | 362 |
| | ZielonaGóra | 13 | 60 | 362 |
| ŁódźVoivodeship | Łódź | 24 | 210 | 775 |
| Lesser Poland Voivodeship | Krakow | 168 | 210 | 25 |
| Masovian Voivodeship | Płock | 8 | 60 | 650 |
| | Radom | 8 | 100 | 1150 |
| | Warsaw | 266 | 1,000 | 276 |
| Opole Voivodeship | Opole | 32 | 60 | 88 |
| SubcarpathianVoivodeship | Rzeszów | 27 | 100 | 270 |
| PodlaskieVoivodeship | Białystok | 15 | 100 | 567 |
| Pomeranian Voivodeship | Gdańsk | 91 | 210 | 131 |
| | Gdynia | 19 | 100 | 426 |
| Holy Cross Voivodeship | Kielce | 12 | 100 | 733 |
| Silesian Voivodeship | Bielsko-Biała | 20 | 100 | 400 |
| | Bytom | 8 | 60 | 650 |
| | Częstochowa | 15 | 100 | 567 |
| | Dąbrowa Górnicza | 6 | 60 | 900 |
| | Gliwice | 28 | 100 | 257 |
| | Katowice | 98 | 100 | 2 |
| | RudaŚląska | 5 | 60 | 1100 |
| | Rybnik | 15 | 60 | 300 |
| | Sosnowiec | 8 | 100 | 1150 |
| | Tychy | 10 | 60 | 500 |
| | Zabrze | 5 | 60 | 1100 |
| Warmian-MasurianVoivodeship | Olsztyn | 11 | 60 | 445 |
| Greater Poland Voivodeship | Kalisz | 16 | 60 | 275 |
| | Poznań | 83 | 210 | 153 |
| Western Pomeranian Voivodeship | Szczecin | 28 | 210 | 650 |

## 6. Conclusions

The Act of January 2018 on electromobility and alternative fuels imposed on municipalities the obligation to launch an appropriate number of publicly accessible charging points in their area. In this study, it was determined that, according to the Act, they must be established only in 32 out of 2477 communes in Poland and they are urban communes. The identification of these communes made it possible to determine the charging station density in their area and the distance between these communes (even 359 km). Based on the analysis carried out, it should be clearly stated that the location of public charging points indicated by the legislator and their number it will not be sufficient to ensure convenient operation of electric vehicles, and the already significant disparities regarding the number of EV charging outlets between agglomerations, smaller towns and rural areas will become even greater. Although the legislator has taken into account construction of EV charging stations along public roads, the conducted analysis has shown that such stations will be installed only along 9 out of 98 existing national roads. However, there will still be areas where the number of publicly available EV chargers will be negligible or there will be no chargers at all (Fig. 13). At the same time, according to Polish drivers, a perfect electric vehicle should be manufactured in Poland, be a four-seater and have a range of 150 km, with a possibility to recharge its batteries every 50 km of the route (KTNS). However, in communes where the minimum number of charging outlets is to be commissioned, on average, 0.75 charger will be available per 1 $km^2$. The highest density will be in Warsaw, i.e. 1.9 charging outlets per 1 $km^2$, however, the smallest density will be noted in Zielona Góra, i.e. 0.22 charger per 1 $km^2$.

Thus it is prudent to create mechanisms supporting construction and operation of publicly available electric vehicle charging stations in Poland. Such support should differentiate between charger types to encourage investors to expand mostly the network of fastest chargers.

The process of constructing an EV charging station involves numerous entities and requires lots of formalities to be dealt with, so the objective should be to streamline procedures in order to limit their negative impact exerted on investment project implementation. An example improvement would be to limit the time required for issuing information (e.g. data regarding the power of connections in existing installations) and for obtaining permits necessary to construct a station. In order to optimise station profitability and decrease the vehicle charging costs, in particular by means of fast and ultra-fast chargers, support for EV charging station operators regarding the necessary adjustment of energy distribution tariffs must be considered. The suggested new tariff should make energy distribution fees conditional only on the energy volume, which will make it possible to adjust the distribution service payment profile to the electric vehicle market dynamics. The positive impact of proper incentives on EVC infrastructure development is illustrated by actions taken by the French government, which, in 2014, reduced tax rates for companies which would install EV charging outlets on their premises. This solution appeared effective, as, already in 2015, the number of EV chargers increased by 482% in comparison with 2014 (Sendek-Matysiak. E., 2018).

All such system solutions supporting and shortening the process of network-related investment projects should encourage EV charging station operators to construct new outlets, particularly in less attractive locations. This is of great importance as, given the locations and the minimum number of publicly available charging outlets in Poland to be established by the 31 March 2021, as indicated by the legislator (according to the Act, the distance between the communes where the minimum number of publicly available charging outlets is to operate reaches even 359 km), it will not be sufficient to ensure convenient operation of electric vehicles, and the already significant disparities regarding the number of EV charging outlets between agglomerations, smaller towns and rural areas will become even greater. Although the legislator has taken into account construction of EV charging stations along public roads, the conducted analysis has shown that such stations will be installed only along 9 out of 98 existing national roads.

However, there will still be areas where the number of publicly available EV chargers will be negligible or there will be no chargers at all (Fig. 13). At the same time, according to Polish drivers, a perfect electric vehicle should be manufactured in Poland, be a four-seater and have a range of 150 km, with a possibility to recharge its batteries every 50 km of the route (INNOGY).

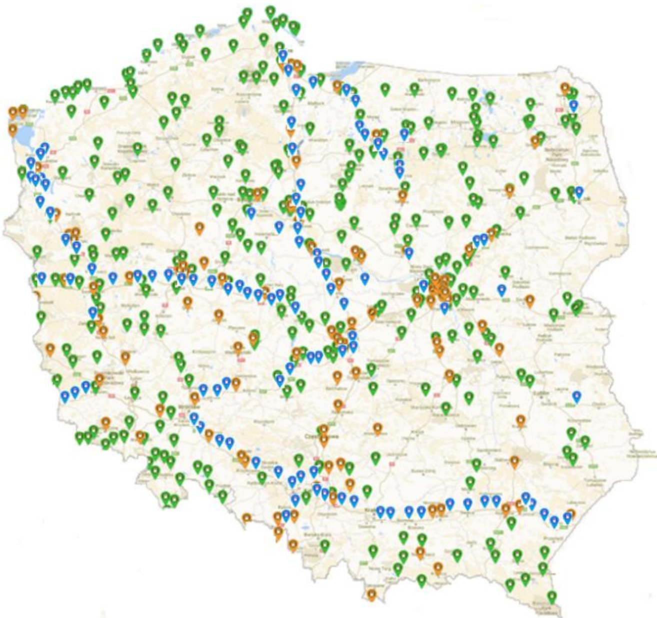

Fig. 13. Map of EV charging outlets in Poland as of 31 March 2021, in line with the provisions of the Act of 11 January 2018 on electromobility and alternative fuels (proprietary compilation based on (ELECTROMOBILITY, 2018; CSO; GDFNR, PSEV))

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# LOGISTICS ENGINEERING AND INDUSTRY 4.0 AND DIGITAL FACTORY

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***Abstract:***

*The number of IT systems and technologies supporting various processes, including the manufacturing, has been growing in recent years. Various versions of integrated ERP-class systems are known. At the same time, we are in the fourth industrial revolution. The future is Industry 4.0 and Digital Factory. Industry 4.0 is an overall term for technical innovations and value change organization concepts which revolutionize the industrial production. Currently, the digital technologies change the way production is carried out by generating, transferring and processing of data, and also by analysing large amounts of datasets. There is a problem of the place and significance of logistics, transport and supply chains in the fourth industrial revolution. What is logistics engineering, what methods are suggested to solve the contemporary problems of logistic support of production processes? To whom are the virtual systems dedicated? What rules should be applied by small and medium enterprises (SME)? Is the pressure of virtual world a threat to such companies? Is it possible to design and make real products without virtual manufacturing? Hence, does Logistics 4.0 exist and where is it used? The practice of logistics engineering is applied during the entire system lifecycle by means of interactive processes supporting the analyses and research (compromise) for optimization of costs, logistics and efficiency. Surely, it can be said that without the correctly designed and effective logistic processes the contemporary production system could not achieve the required productivity and effectiveness. The article describes the basic tasks of logistics engineering in relation to production companies, as well as relations with Industry 4.0. and digital factory. Moreover, a proposal of the author's own algorithms for use in the quest to improve the continuity of flow and of enterprise effectiveness for SME class companies was presented.*

***Keywords:*** *logistics engineering, supply chain, production logistics, Industry 4.0*

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## 1. Introduction

The development of supply chain concepts in recent years gave a wider view of the logistics. First of all, it transformed the companies from functionally oriented organizations to process-oriented organizations (Dolgui and Proth, 2010). An important thing is that the shift towards the processes applies not only to single companies, but to all supply chain links. The common element linking various approaches to logistics is material flows which should be competently managed (Taylor, 2009). Currently, due to the fourth industrial revolution Industry 4.0, the importance of logistics has increased and the requirements for logistic systems have grown (Biffl et al., 2017).

There are two main areas in which logistics is necessary for effective operation of production systems:

- supply of components necessary for production of goods (supply chains);
- material flows in complex production and assembly systems (production logistics).

Meanwhile, the terms appearing in publications on the fourth industrial revolution bewilder with modern technologies, inter alia Internet of Things, Artificial Intelligence (AI), Smart Factory, cloud computing, additive manufacturing (3D printing), smart supply chains, and cyber-physical systems. Each of these areas already has methods and tools for execution of specific processes (Pinto et al., 2018). The fourth industrial revolution (Industry 4.0) is largely based on mutual use of automated collection, processing and exchange of data from the entire supply chain. However, a company intending to be transformed into an Industry 4.0 company first needs to put its processes in order and then start collecting data about the deviations in these processes. Automation offers PLCs, multiaxial motions sensors, HMI operator panels (Bauernhansel et al., 2014). It is necessary to implement new IT solutions (e.g. Manufacturing Execution System MES or Warehouse Management System WMS). The result of implementation of Industry 4.0 ideas is an intelligent factory based on the integration of cyber-physical systems using industrial internet of things (IoT). The digital factory changes not only the production range of companies, but requires a holistic view of the business ecosystem, e.g. value chains or supply chains (Kuehn, 2018).

Contemporary production systems, driving for high productivity, require a very good logistic support. According to Bukowski (Bukowski, 2016), one of the most important objectives of strategic and operational supply chain managements should be the Supply Chain Risk and Continuity Management, with a particular emphasis on safety, dependability and maintaining the supply continuity in crises (resilience).

In case of large companies, where production requires many components, the supply chains are very complex. The requirements for contemporary supply chains are very high and related to many aspects. A systems approach to the logistic process design is suggested by Jacyna and Lewczuk (Jacyna and Lewczuk, 2016). The transport is an important element in supply chains and transport planning requires the use various models, often simulation models (Jacyna et al., 2019). Another very important task is evaluation of supply chain effectiveness. Jacyna-Gołda suggests (Jacyna – Gołda, 2016) single- and multicriterial decision models allowing the effectiveness evaluation in the technical, economic and quality aspects (Jacyna – Gołda et al., 2018).

Kuehn (Kuehn, 2018) believes that the complexity of contemporary production and logistic systems requires multicriterial decision indicators. In relation to contemporary digital enterprises Kuehn suggests a systemic approach to the value chain optimization. By use of integrated software solutions, a digital image of entire value chains can be created.

## 2. Industry 4.0 and logistics engineering – literature review

Recent years have brought an increasing amount of information and publications related to the fourth industrial revolution. As usual, when something new appears, we get a lot of incomplete and not fully true information, in this case mainly related to the understanding of process virtualization (virtual factory, virtual production). The problem is important as the fourth revolution encompasses a broad area of new technologies affecting not only the industry, but also many other areas of life.

A succinct description of the fourth revolution is given by company Astor in its publication (Gracel et al., 2017):

> ‘Industry 4.0 is an overall term for technical innovations and value change organization concepts which revolutionize the industrial production. Currently, the digital technologies change the way production is carried out by

> generating, transferring and processing of data, and also by analysing large amounts of datasets. The use of these opportunities requires digitalization, i.e. the change of the data collection and processing from analogue to digital. The other revolutionary aspect is the possibility of uniting and interaction of two worlds, the virtual and the physical.'

Schwab (Schwab, 2016) gave a very good description of the fourth industrial revolution. It is worthwhile to quote his words from the preface to The fourth industrial revolution:

> '…Of the many diverse and fascinating challenges we face today, the most intense and important is how to understand and shape the new technology revolution, which entails nothing less than a transformation of humankind. Consider the unlimited possibilities of having billions of people connected by mobile devices, giving rise to unprecedented processing power, storage capabilities and knowledge access. Or think about the staggering confluence of emerging technology breakthroughs, covering wide-ranging fields such as artificial intelligence (AI), robotics, the internet of things (IoT), autonomous vehicles, 3D printing, nanotechnology, biotechnology, materials science, energy storage and quantum computing, to name a few. We are witnessing profound shifts across all industries, marked by the emergence of new business models, the disruption of incumbents and the reshaping of production, consumption, transportation and delivery systems.'

In relation to production processes, the cyber-physical production systems(CPPS) are rather well diagnosed. Kuehn wrote about digital factories and production planning simulation already in 2006 (Kuehn, 2006 a, 2006 b). The general foundations of new technologies used in Industry 4.0 are described inter alia by Bauernhansel (Bauernhansel et al., 2014) dealing mainly with the processes of production, automation and logistics. The table presenting the development stages of production and logistics taken from this publication shows very well the challenges related to the Industry 4.0 technologies (Tab. 1).

A broader, multidisciplinary approach to cyber-physical systems is presented by Biffl, Lüder and Gerhard, paying special attention to the complexity of design processes (Biffl et al., 2017). The book is a practical manual of production system modelling based on the Product Lifecycle Management (PLM), Production System Engineering (PSE) and on modelling of the IT systems integrated with physical systems.

In a more market-oriented approach proposed by Nyhuis and Wiendhal (Nyhuis and Wiendhal, 2009), the production as a basic function used to fulfil orders for specific products is increasingly used to improve the company's effectiveness on the market. In addition to high standards in terms of product quality and process, the logistic factors: delivery dates and capability of fulfilling and reliability of deliveries can gradually become the possibilities for market differentiation.

> …'The goal therefore, is to organize the entire material flow in the supply chain, from procuring raw materials and preliminary products, through the entire production process including all of the interim storage stages, up to supplying distributors or as the case may be, external customers in such a way that the firm can react to the market in the shortest time span'.

In relation to supply chains, Nyhuis and Wiendhal write directly that:

> …'The fundamental goal of production logistics can thus be formulated as the pursuance of greater delivery capability and reliability with the lowest possible logistic and production cost'.

Therefore, the long-term market success is decided by production costs, reliability and possibility of deliveries.

Table 1. Stages of production and logistics development on the way to Industry 4.0 (acc. [1])

| | **Yesterday, previously (Industry 1.0/2.0)** | **Today, now (Industry 3.0)** | **Tomorrow, future (Industry 4.0)** |
|---|---|---|---|
| Supersystem | Analog communication | Internet and Intranet | Internet of Things (IoT) |
| System | Neo – Taylorism<br>TRS (TUL) - Processes | Lean Produktion<br>Lean Logistics | Smart Factory<br>Cognitive Logistics |
| Subsystem | Mechanization | Automation | Virtualization |

Very interesting and effective solutions for systemic approach to processes within Industry 4.0 is proposed by Siemens. The fourth industrial revolution is a concept of using automation and data processing and exchange, and also implementation of various new technologies allowing the creation of the so-called cyber-physical systems and change of production methods. It is also related to the production digitalization, where technological equipment and systems communicate with each other, also via the Internet, and where large amounts of production data are analysed. Industry 4.0 is here an aggregate term encompassing a number of new technologies, i.a. Internet of Things, cloud computing, Big Data analysis, artificial intelligence, 3D printing, enhanced reality or collaborative robots. The basic processes related to the transformation of companies operating in accordance with Industry 4.0 to digital companies are described by Mychlewicz and Piątek (Mychlewicz and Piątek, 2017). Twin interconnections of virtual and real processes proposed by Siemens is presented in Figure 1.

The approach proposed by Siemens is known as the Digital Enterprise Suite (DES). The Digital Enterprise Suite offers integrated software and hardware solutions for discrete industries to seamlessly integrate and digitalize the entire value chain, including suppliers. With the Digital Enterprise Suite Siemens integrates Product Lifecycle Management (PLM), Manufacturing Operations Management (MOM), Totally Integrated Automation (TIA) – all based on collaboration platform Teamcenter and being connected to MindSphere: cloud – based and open IoT operating system.

### 2.1. Logistics engineering in production systems

Many papers on logistics in companies focus on the processes related to orders, supply of materials, purchases, storage and distribution of products. However in a production company, the most capital-intensive process is the manufacture of goods. The manufacture makes the material stream flow through individual production cells (stations) in a company. This flow depends on many factors, of which the production system structure is absolutely the most important. A skilful use of quantitative methods proposed by contemporary science and technology is necessary in order to determine the company key performance indicators. In Logistics engineering handbook (Taylor, 2008) Taylor wrote:

> ‘It is a fact that there are a few, if any, significant differences between the business logistics and logistics engineering, except the fact that the logistics engineers often use more ‘mathematical’ or ‘scientific’ methods in logistic application. In the search for logistics solutions, the future challenge is a broader understanding of the logistics which is reflected by the systemic approach.’

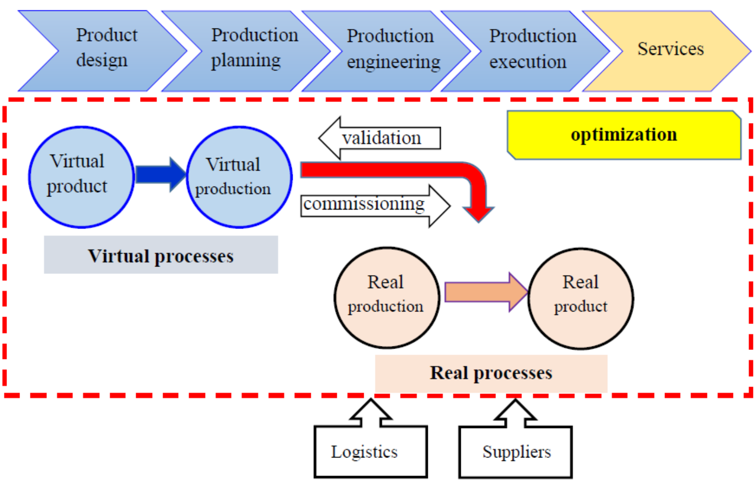


Fig. 1. Twin processes in the Industry 4.0 concept (own study based on Siemens materials)

Hence, new concepts and tasks of production logistics appear. As a method for waste elimination (muda), Womack and Jones (Womack and Jones, 2008) recommend lean approach, lean thinking by creating the value stream in a company. In the simplest words, the lean actions can be described as processes of continual elimination of waste. In such approach, the most important task in production systems is to maintain continuity in material flows (Rother and Harris, 2007), and also permanent improvement (kaizen) of continuity. The term logistics engineering is relatively rarely used in Poland, unlike the USA where the logistics engineering is widely used to solve various problems related to the design and implementation of logistic processes (Michlowicz and Mindur, 2018).

According to the Council of Logistics Engineering Professionals – CLEP: Logistics Engineering: The professional engineering discipline responsible for the integration of support considerations in the design and development; test and evaluation; production and/or construction; operation; maintenance; and the ultimate disposal/recycling of systems and equipment. Additionally, this discipline defines and influences the supporting infrastructure for these systems and equipment (i.e., maintenance, personnel, facilities, support equipment, spares, supply chains, and supporting information/data). The practice of logistics engineering is exercised throughout the system life-cycle by conducting the iterative process of supportability analysis and the accomplishment of trade-off studies to optimize costs and system, logistics, and performance requirements.

Logistics engineering as a discipline is a very important aspect of systems engineering that also includes reliability engineering. It is the science and process whereby reliability, maintainability, and availability are designed into products or systems. It includes the supply and physical distribution considerations above as well as more fundamental engineering considerations. Logistics engineers work with complex mathematical models that consider elements such as mean time between failures (MTBF), mean time to failure (MTTF), mean time to repair (MTTR), failure mode and effects analysis (FMEA), statistical distributions, queueing theory, and a host of other considerations.

The task of the logistics engineering in a company is to develop and prepare a system of acting, which using the laws and rules of logistics and also other sciences, will allow implementation of the logistic tasks supporting the achievement of effects specified in the company strategy. The actions should focus on 'how'.

– how the product is made;
– how the service is provided.
– The basic strategies may include:
– high customer service quality;
– World Manufacturing Class - WMC;
– desired (specific) productivity;
– obtaining specific business and technical indicators.

The logistic methods and tools useful in company logistics are generally known (Michlowicz, 2013). Their application depends (in addition to the adopted strategy) on potential, knowledge and skills of the technical and managerial team and the area of actions. The choice of the area and the tasks implementation methods are the first, very important stage of actions aiming at the achievement of desired effects. In relation to the new requirements connected with the fourth industrial revolution, the lean methods have become particularly important. Very interesting theoretical foundations necessary to understand the correct use of lean methods in modern manufacturing are presented by Ruttiman (Ruttiman, 2018) in the monograph Lean compendium. Introduction to modern manufacturing theory. Similar changes can be observed in the understanding of the Just in Time systems. The authors of Just in Time Factory. Implementation through lean manufacturing tools (Pinto, Matias, 2018) present new areas of JiT application in manufacturing systems.

The most often used lean methods include:

– VSM Value Stream Mapping;
– TPM Total Productive Maintenance;
– 5 S - 5 Pillars of the Visual Workplace – workplace visualization and standardization;
– SMED Single Minute Exchange of Die;
– JiT Just in Time – just-in-time flows;
– Kanban – organization and control with the use of cards;
– 5W1H - 5 why and 1 how – knowing the problem cause;
– 7 M - 7 Muda, 7 Wastes – waste elimination in processes;
– Heijunka – Sequencer – sequencing of production;

- Jidoka - Autonomation – possibility of stopping the line or process;
- Kaizen – evolutionary continuous improvement;
- Kaikaku – innovation, rapid change for the better.

In addition to methods known as lean tool box (recently more often - lean tool system), the logistics engineering proposes an analysis of manufacturing processes using the production logistics laws – PLL which describe relationships between individual production process parameters (Table 2).

Table 2. Production Logistics Laws PLL (acc. [18])

| | |
|---|---|
| **1_PLL** | In a long timeframe the material input level and output level to/from the station must be balanced. |
| **2_PLL** | Time of material passage through the station depends on the proportion of work in process (WIP) and the rate of leaving the process. |
| **3_PLL** | Reducing the station use levels allows a disproportional reduction of WIP and shortening the time of material passage through the station. |
| **4_PLL** | Variance and average value of the labour intensity define the logistic potential of the station. |
| **5_PLL** | The size of WIP buffer required to ensure the appropriate station use level depends mainly on the load flexibility and station capacity. |
| **6_PLL** | If the orders are performed according to the FIFO principle, the time between operations does not depend on the labour intensity of individual operations. |
| **7_PLL** | Application of sequencing rules can significantly affect the average passage time only at a high WIP level and a wide distribution of labour intensity of individual tasks |
| **8_PLL** | Passage time variance depends on the applied sequencing rules, WIP level and the distribution of labour intensity of individual tasks. |
| **9_PLL** | The logistic process reliability is defined by the average value and the distribution of material flow time through the system. |

The contemporary concepts focus on methods to minimize the WIP (Work in Process) level (e.g. Ruttiman, 2018), and also on reducing and unifying the passage times and making the Work Content structure more uniform. Particularly important are relationships between the WIP level, minimization of processing times and material passage times through equipment and the level and reliability of deliveries. LOC (Logistic Operating Curves) can be used to solve possible conflicts. The curves are measured for all correlations between a selected parameter (goal or variable) and the independent variable (e.g. curve: passage time – WIP) or storage costs – resources). Additional curves accounting for logistic processes in the system include:

- POC – Production Operating Curves;
- TOC – Transport Operating Curves;
- SOC – Storage Operating Curves.

In relation to complex systems in which many different products are made and production is not mass, reliability theories, queue theories or other stochastic theories are often used (e.g. Zwolińska, 2019). Other quantitative solutions are proposed by various disciplines more loosely related to the logistics, inter alia:

- operational research (OR);
- artificial intelligence (AI);
- information technologies (IT).

Figure 2 presents logistics engineering methods which can be used in production companies.

## 2.2. Solving supply problems in distribution systems

The goal of the distribution is to deliver to the final customers the product they need (type, quantity), to the places where they want to buy such products, at the time they want to buy them, at agreed terms and at the lowest price possible. Therefore, the logistic operator faces the task to develop such transport plan that would give optimum results due to the optimizing criterion used. In addition, there are often other problems to be solved, inter alia:

- minimization of transport lead times;
- shaping the transport network;
- distribution of transport stream in the network;
- selection of technical equipment and determination of potential of transport and logistics systems.

The real logistic systems have many limitations not accounted for by typical algorithms, such as imposed delivery time, capacity of vehicles, sizes of load units. As a result, new algorithms are continuously being searched for to support the achievement of complex tasks of logistic operators (Michlowicz, 2017).

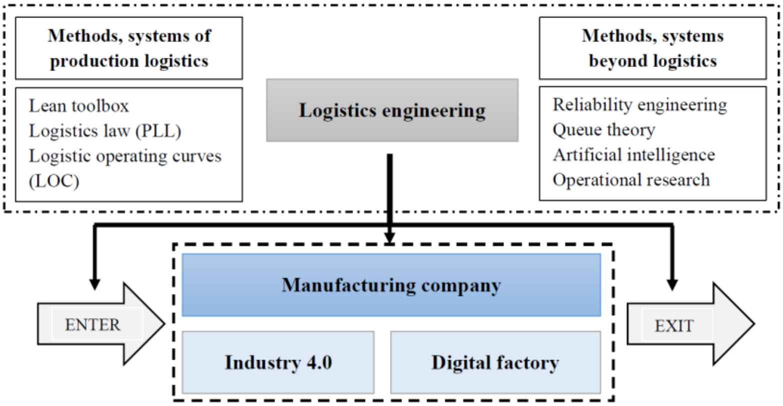


Fig. 2. Logistics engineering in a company (own study)

The best known, typical VRP (Vehicle Routing Problem) involves minimization of transport costs from one warehouse to any number of recipients (customers). Currently, there are a lot of delivery problems. The best known include:

- CVRP (Capacity Vehicle Routing Problem) – all vehicles have identical capacity;
- VRPTW (Vehicle Routing Problem with Time Windows), extension of CVRP to include time windows for each customer (time interval during which the customer can be served);
- SDVRP (Site-Dependent Vehicle Routing Problem), extension of CVRP; vehicles have different capacities; hence limitations in providing service for some customers;
- MDVRP (Multi Depot Vehicle Routing Problem), there are many central depots;
- MDVRPTW (Multi Depot Vehicle Routing Problem with Time Windows);
- VRPSD (Vehicle Routing Problem with Stochastic Demands);
- RDPTW (Rich Delivery Problem with Time Windows), there are defined time windows for customers, the load unit weight is defined, and vehicles have different capacities.

Various hybrid algorithms are used to solve such complex problems. These are most often genetic, evolutionary, adaptive algorithms of searching large ALNS (Adaptive Large Neighbourhood Search), simulated annealing heuristics, and ant algorithms (Ant Colony Systems). The task costs are a very large limitation in the distribution systems. At least 3 cost groups should be considered:

- distribution network maintenance costs;
- transport costs;
- storage costs.

In solving such problems, the methods based on probability theory and stochastic laws are increasingly used, as suggested by the logistics engineering (Zwolińska, Michlowicz, 2016). It is obvious that to solve such problems one must have sufficiently large databases and use ICT (Information Communication Technology) resources.

## 3. Problem of Polish SMEs. Is Industry 4.0 a threat?

The structure of Polish economy by the basic type of operations is as follows (Zakrzewski, 2019):

- services 52.3 % (including transport and storage – 7.5 %);
- commerce 24.0 %;
- construction 13.6 %;
- industry 10.1 %.

Fundamental questions arise:

‘to what group of companies does the Industry 4.0 idea apply?’
‘will CPPS (Cyber-Physical Production Systems) be used at small and medium enterprises?’
‘which elements of Industry 4.0 should be used at SMEs?’

An extensive report in a PARP (Polish Agency for Entrepreneurship Promotion) (Zakrzewski and Skowrońska, 2019) indicates that in Poland large companies which absolutely should transform towards Industry 4.0 are only 0.2 % (3600 units) of all companies (more than 2 070 000 units). At the same

time, these companies generate 23.8 % of GDP and employ 3.1 million people which is 31.6 % of total employment at Polish companies.
On the other hand, micro and small companies employ 52.1 % of all employees, and their share in GDP is 38.7 %. It seems that the problems with implementation of the fourth industrial revolution technologies in this group are related only to selected technologies (Internet, cloud).
The biggest problem with the Industry 4.0 implementation is at the medium-sized companies. They are 0.7 % of all Polish companies (15 000 units) and generate 11.1 % of Poland's GDP. An average company employs 105 people. Thus, these are companies for which the Industry 4.0 technologies should be thoroughly analysed and implemented (strategic and cost-effective).
Selected characteristics of Polish companies are presented in Table 3.
Figure 3 illustrates the selected characteristics in the context of supplies necessary for achievement of tasks in such companies.
Please note that among all Polish companies (2 073 600 units) transport and logistic companies are 7.5% and industrial companies 10.1%.

## 4. Efficiency improvement algorithm – solution for SMEs

Currently, the key to understanding the operations of a company is the awareness, that it functions as a part of a larger system. The development of the SCM concept forces the companies to transform from functionally-oriented to process-oriented organisations. The common element, shared by different approaches to logistics are material flows and their skillful management.
Figure 4 presents a simplified diagram of a system comprising processes implemented in production companies, with particular emphasis on the logistic and storage processes.
Implementation of individual tasks (acc. to Fig. 4) requires a specific strategy. The basic tasks necessary for implementation in order to improve the production system performance in such a system are presented in Table 4.

Table 3. Selected characteristics of Polish companies (own study acc. to [25])

| Type | Sector share – quantitative [%] | Employment [M people] | Own website [%] | Cloud computing [%] |
|---|---|---|---|---|
| Micro and small | 99.1 | 5.1 | 62.5 | 7.2 |
| Medium | 0.7 | 1.6 | 84.5 | 19.0 |
| Large | 0.2 | 3.1 | 91.1 | 42.7 |

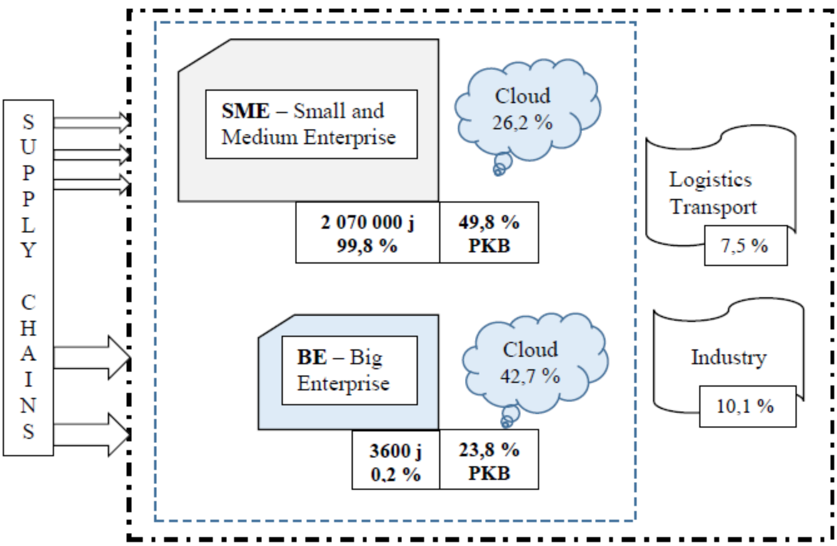


Fig. 3 Selected characteristics of Polish companies in context of supplies (own study)

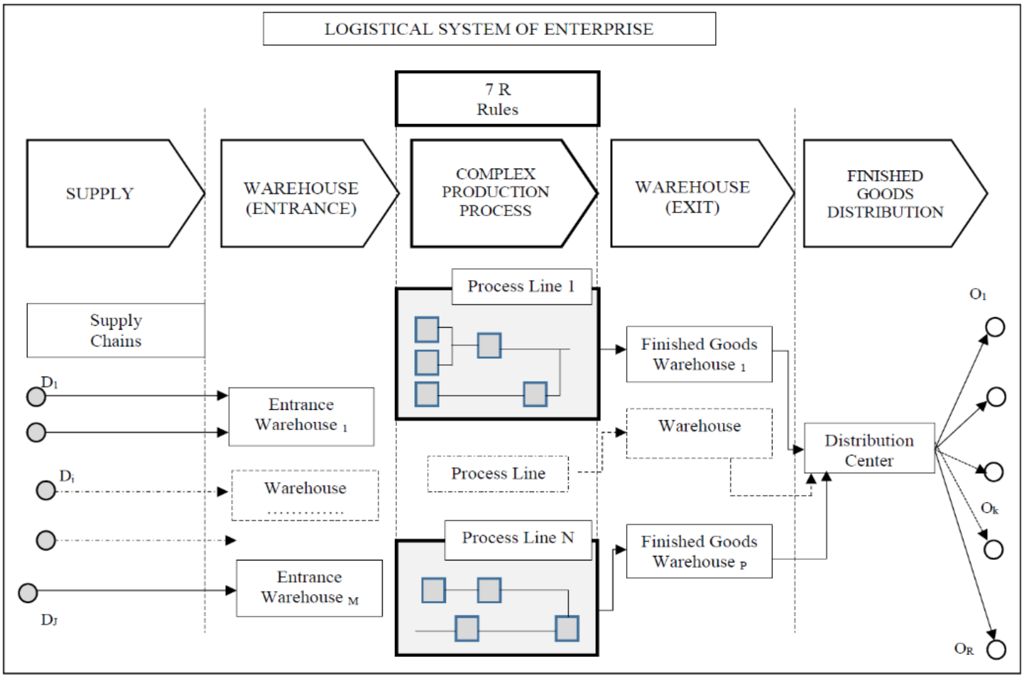


Fig. 4. Diagram of logistic and production processes in a company (own study)

Table 4. Tasks for implementation in a production system (acc. to Fig. 4)

| Basic tasks for implementation | | | | |
|---|---|---|---|---|
| Supply strategy<br>- selection of suppliers | EN storage strategy<br>- input warehouses,<br>- storage area | Manufacturing strategy<br>- material flow continuity | EX storage strategy<br>- finished goods warehouse,<br>- storage area | Distribution strategy<br>- distribution channels,<br>- distribution strategy |
| Classification of components<br>- ABC, XYZ, Pareto | Reception technology,<br>- identification | Production logistics laws<br>- 9 PLL | Inventory analysis | Order picking |
| Forecasting | Inventory model | work in process -WIP | Storage strategy | Shipment and customer service model |
| | Placement<br>- ABC | lean toolbox<br>- JiT, VSM, TPM... | Means of transport | Reverse logistics |
| | Means of transport | ZSI<br>- ERP, MES,… | | Optimization<br>- VRP,… |
| IT support – common hardware and software platform / Effectiveness evaluation indicators | | | | |

The analysis of Figure 4 and strategy from Table 4 indicates that one of the most important tasks in a company is to maintain the continuity of material flow (including information). The discontinuity of material flow can be caused by two main reasons:

– Absence of components in the areas of processing or assembly – logistics most be improved.
– Low availability of machinery and equipment – maintenance must be improved.

Implementation of single lean components (e.g. 5S, JiT, Kanban, SMED, TPM, VSM) is just a beginning of the road to the full concept. The true challenge is to see the whole process. In case of companies, particularly SMEs (Small and Medium Enterprises), it could be very difficult to see the whole process, so the only option left is to implement single elements. For that road to lead to synergy, it is worthwhile to build a system of goals for a longer timeframe and set individual stages for this period. Quick effects are obtained e.g. by eliminating waste (7 Muda) and organization according to the 5 S rules.

The implementation processes are always accompanied by the value stream. The value stream is a set of all actions required to make a product. The value stream visualization allows seeing all waste in it and aiming further 'leaning' actions at eliminating waste from the areas that add value – the VSM (Value Stream Mapping) method.

TPM - Total Productive Maintenance – is one of the most important tools of lean management of manufacturing processes. The TPM goal is to maintain the continuous operation of equipment and machines that perform specific tasks, which at the same time improves their operational effectiveness.

The experience of the author enables the conclusion that the task of introducing the improvement of continuity can be described in several stages.

At the first stage, a very precise identification of all processes associated with production and logistics is required. After identifying and determining the actual purpose of improving production efficiency, the proper choice of methods and tools to achieve these goals should be initiated.

Thus, the initial activities include two stages:

Stage I – identification of the process – activity: 1, 2, 3, 4.

1. Selection of the process for analysis.
2. Drawing up an accurate diagram of the technological process.
3. Collection of data on the process, including orders, deliveries, inventories, etc.
4. Determination of basic parameters and values describing the process, execution of the necessary timekeeping for the timing of operations.

Stage II – The choice of methods and improvement tools (e.g. VSM, TPM) – actions: 5, 6.

5. Description of losses and waste in the process (e.g. 7 muda, 6 big losses).
6. Tool selection.

Figure 5 shows the first two stages of an algorithm for improving efficiency in the production system.

The consecutive steps necessary to achieve the desired improvement of the functionality (effectiveness) of the operation, as well as to ensure the continuity of the flow of materials, depend on the choice of method (tool).

If the VSM (Value Stream Mapping) mapping method is chosen, the algorithm is described by the successive stages III, IV and V.

Stage III – elaboration of the map of the existing state – actions: 7, 8, 9, 10.

7. Development of icons for the process.
8. Preparation of a map of the existing state (readable and in an appropriate format, such as A2).
9. Determination and collection of information about possible proposals for changes to the existing system.
10. Plotting the proposed changes on the value stream map.

Stage IV – introduction of changes – actions: 11, 12.

11. Preparation of arrangements and deadlines for possible changes.
12. Introduction of changes.

Stage V – analysis of results and improvement – actions: 13, 14.

13. Analysis of the effects after introducing the changes.
14. Insistent implementation of the principles of kaizen!

Figure 6 illustrates the stages of an algorithm utilising the VSM mapping method.

As was true of the TPM method, the algorithm takes stages III to VI into consideration.

Stage III – identification of the functioning of machinery – actions: 7, 8, 9.

7. Identification of failures and downtime.
8. Plotting of Pareto diagram – causes of failure. Selection of the reasons for improvement.
9. Determination of objectives – limit values of MTTR and MTBF.

Stage IV – determining the OEE efficiency ratio – actions: 10, 11, 12

10. Determination of the availability indicator for the lines (available time net, working time).
11. Determination of the process efficiency ratio (achieved efficiency, nominal efficiency).
12. Determination of the quality indicator (achieved quality, desired quality).

Stage V – introduction of changes – actions: 13, 14

13. Development of time schedule for implementing changes in the area of reducing the number of machine failures.

14. Introduction of changes aimed at improving the indicators of availability, efficiency and quality (of machines involved in the process).

Stage VI – analysis of results and improvement – actions: 15, 16.

15. Analysis of the effects after introducing the changes.
16. Insistent implementation of the principles of kaizen!

Figure 7 illustrates the stages of an algorithm utilising the TPM method.

These two exemplary methods are very often used in manufacturing companies. The experiences of companies that strive for continuous improvement of productivity show that the onset of improvement should be the implementation of the principles of '5S' (5 Pillars of Workplace Visualisation).

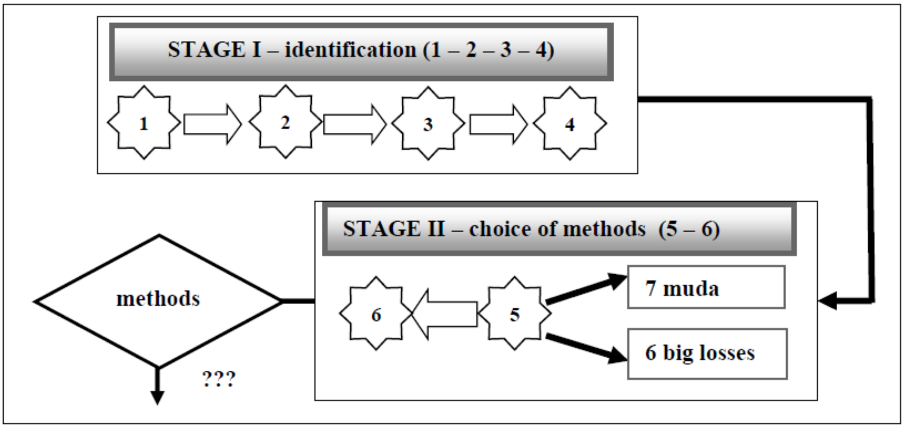


Fig. 5. Algorithm - choice of methods for improvement

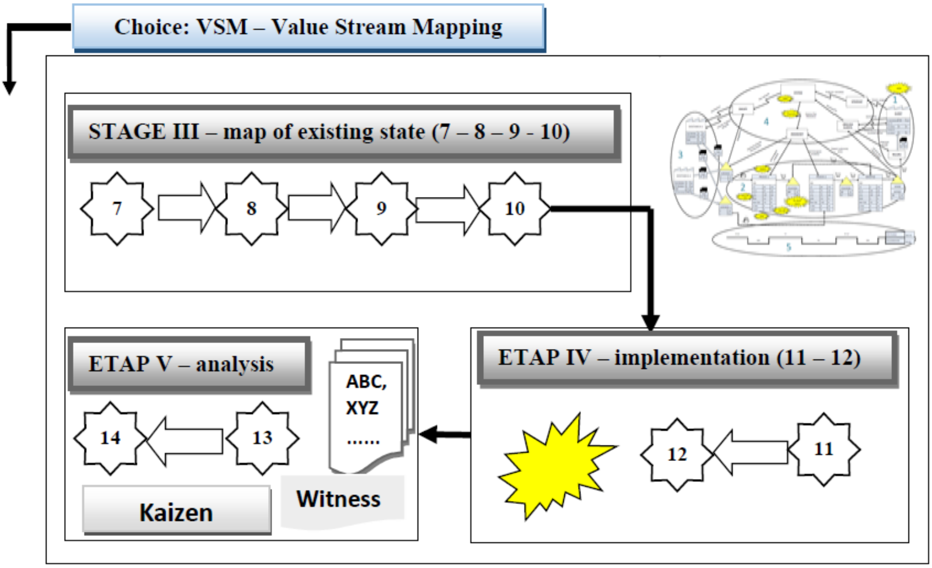


Fig. 6. Algorithm - improvement via the VSM method

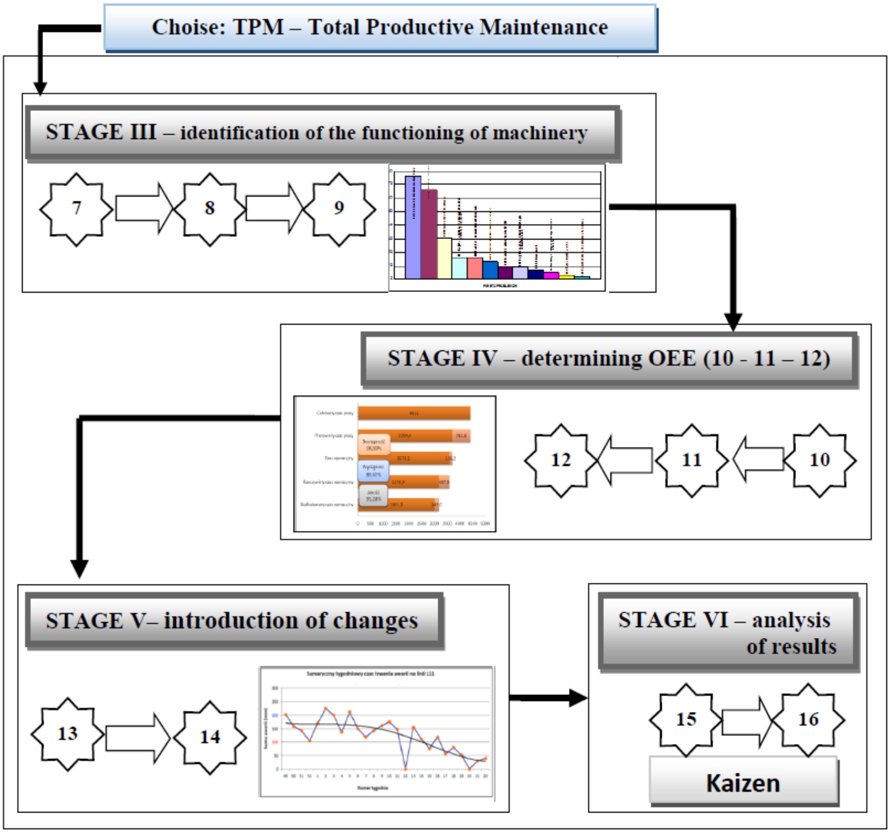


Fig. 7. Algorithm - improvement of performance using the TPM method

## 5. Conclusion

The fourth industrial revolution – Industry 4.0 – requires the use of many information technologies and also cyber-physical production systems (CPPS). It is frequently noted now that the Industry 4.0 is being transformed into Digital Factory and Smart Factory. The key question is to which companies such transformations apply. It is beyond doubt that the changes mainly apply to large companies (in Poland they are 0.2 %, that is 3600 companies) and some medium ones (in Poland medium companies are 0.7%, that is 15 000 units). However, in all modern enterprises, the logistics competence covers an increasing large area. Broadly understood supply chain and production management now suggests many various methods and techniques for improved operation of logistic systems. Some such methods have been developed within Lean Management. Systems for material flow organization and control and ERP integrated IT systems are widely known. Production logistics also faces these challenges. Value steam improvement by VSM and ensuring high availability of machines by means of TPM are oftener and oftener used at production companies. In many areas very helpful are production logistics laws (PLL) and original flow analysis algorithms. The development of theories related to supply chains and lean thinking forces the companies to go beyond their boundaries. This leads to a systemic approach to the problems related to the designing of logistic processes. Logistics engineering is a discipline which, by integrating many processes, using mathematical methods and achievements in the studies on broadly understood logistic processes, allows practical solutions to be found.

For many companies, especially Small and Medium Enterprises (SME), the complete capture of the process may prove to be too difficult. Therefore, the way to implement individual elements of lean methods remains. In order for this path to result in synergy, it is worth building a system of goals for a longer period of time and for this period to set individual stages. VSM (Value Stream Mapping) and TPM (Total Productive Maintenance) are very useful methods for SME class enterprises. The algorithms presented in the article can be directly used to improve efficiency in SME class enterprises.

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# THE RAILWAY OPERATION PROCESS EVALUATION METHOD IN TERMS OF RESILIENCE ANALYSIS

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## *Abstract:*

*In complex socio-technical systems there is an influence of safe unwanted events on the occurrence of accidents. It is like domino bricks. Therefore, it is not only the recovery from major events that is important, but also the recovery from disruptions in operation. As the literature review shows, the recovery of operation processes is analysed by single criterions for small disruptions. On the other hand, resilience research is focused on the network and major events, but not on frequent small-consequence events that affect operational processes. The performance of a system is a key parameter when evaluating resilience. As a result of the performed literature survey, the aim of the paper was to propose a new method for evaluating performance in terms of operational processes and resilience analysis. Moreover, it is also important to order the most important terms related to this issue, as well as to introduce new types of qualities, which are not only focused on the system, but also on the implemented operational processes.*

*The paper consists of eight sections. The introduction section describes generally the problem, that leads to formulation of the aim of the paper and description of its structure. It is followed by the second section consisting of a complex literature survey. Section three orders the reliability, robustness and resilience definitions. Section four analyses the performance influencing factors using Fault and Event Tree Analysis, while section five defines the operational layer of the system and shows a formal description of operation processes. Section six presents the operation process evaluation model. It was elaborated using the Fuzzy Logic approach, that allows combining of incoherent system and process qualities: punctuality, probability no further delays, quantitative implementation of scheduled processes, reconfiguration level. Afterwards a case study is shown to present the method application. The performed case study shows the advantages of the proposed approach, which is related to the most common methods. The paper ends with conclusions and further research perspectives.*

***Keywords:*** *railway, resilience, performance, Fuzzy Logic*

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## 1. Introduction

The railway transport system can be defined by diverse qualities. The most common general qualities were identified by Jacyna in 2009 as: the railway network, rolling stock, the timetable, passengers and freight. The timetable is related to all of these issues and creates the relation between the network and rolling stock. It includes boundaries, and it should be adequate to fulfil market demand. Boundaries are interpreted as the relationship between systems with respect to their states (Johansson and Hassel, 2010). Models normally take into account arc capacities in order to describe the performance of the rail system (Johansson and Hassel, 2010). The most undesirable events in the rail system result in delays. About 98% of all unwanted events in the rail system end in so-called safe consequences (Restel et al., 2019), and there is therefore no further investigation.

Nevertheless, there is an influence of safe unwanted events on the occurrence of accidents. It is like domino bricks. Thus, it is not only the recovery from major events that is important, but also the recovery from disruptions in operation. These issues are typically not taken into account during the evaluation of resilience. Improving disruption recoverability can be a key factor in accident prevention. During previous researches, it was proven that small consequence events definitely have an influence on the occurrence of accidents (Restel, 2014).

It can be stated that it is not enough to keep the correct capacity of system branches, but it is also necessary to maintain the process schedule. Thus, the need arises to go beside the classic approach focussed on the network (system) resilience. The concept of operational resilience can fill the existing gap. Foster et al., (2019) stated that such an approach will be helpful in decision-making for adaptation processes. Patriarca et al. (2018) concluded from their performed literature review that the creation of simple and universal methods for the assessment of resilience is not possible for different types of complex sociotechnical systems. Therefore, the aim of the paper is to propose a method for evaluating the operation process as a part of further resilience investigation. More detailed goals are presented after the literature research. The paper contains eight sections, including the introduction and conclusions. The literature review shows the gap which will be filled by this contribution, as well as the starting level in terms of approaches and concepts. It is followed by an ordered description of resilience and robustness concepts, and also an analysis of performance influencing factors. Then, a description of both the operation process and the model is followed by a case study. The conclusions highlight the most important issues and summarize plans for further research.

## 2. Literature research

Articles referring to timetable issues and its evaluation are focussed on disturbances. Unfortunately, the sources and impact of disturbances of diverse types of failures are not classified (Kroon et al., 2007, Solinen, 2017). The evaluation of system operation uses diverse indicators for finding the best alternative for dispatching. Waiting times and arc capacities are mainly used for evaluating timetable stability and efficiency (Buchel and Corman, 2018, Pachl, 2016). The evaluation of reconfiguration scenarios and strategies results in the finding of the best solution in terms of a given goal function. The given approaches are mainly based on only one evaluation criterion (Andersson et al., 2013, Louwerse and Huisman, 2014), however, the consequences of reconfiguration are not taken into account.

A lot of effort has been put into diverse optimization models (Jacyna and Golebiowski, 2015). Their development was focussed on supporting the decision making process after the occurrence of disruption. Literature reviews on this subject were performed by Yang et al. (2016). Railway problems are treated separately by various authors. For example, there are separate views on the timetable (Yang et al., 2014), the optimization of train movement (Yang et al., 2012), or risk management (Azad et al., 2016). Therefore, solutions to the problems are limited by a given perspective. The optimization criteria are therefore rather limited and one dimensional e.gen-ergy consumption (Yang et al., 2016, Urbaniak et al., 2019) or the travel time in a given network (Al Khaled et al., 2011). On the other hand, models that use more than one parameter for solving railway problems can also be found (Wang et al., 2015, Jacyna and Golebiowski, 2016). These approaches are dedicated to undisrupted operation. Moreover, they are mainly focussed on network capacity or energy consumption.

Robustness is a quality related to withstanding against undesired influences. It is described in a couple of different ways, which both differ in terms of meaning. Robustness is known as the ability of a human-technical system to withstand inaccuracies (Salido et al., 2008). It can also be the system's ability to withstand trouble with no significant changes in the operation processes (Takeuchi and Tomii, 2005). Policella (2005) understands it as tolerance for undesirable events. However, the later on robustness is defined in terms of recovery time.

Dewilde et al. (2011) use robustness to assess timetables. It is defined as the ability of minimizing passenger travel times if small disruptions occur. The assumption was also made that the delays and recovery times are limited by fixed maximum values. Schobel and Kratz (2009) quantify robustness using the maximum value of primary delays that will not affect any passenger transfers. Goverde (2007) sees timetables as stable if delays do not propagate between assumed time periods. Goverde (2008) also introduces locally or globally stable systems. Stability means that primary delays have to be compensated in a finite time (Andersson et al., 2013).

Timetables can also be called robust if disruptions do not create delays (Kroon et al., 2008b). Moreover, the timetable will also be seen as robust if initial delays will be made up for as fast as possible, if the number of secondary delays is very small, and if almost no dispatcher actions are necessary to recover the system operation. Dispatcher operations were analysed by Lu et al. (2017). Departure time, the possibility of overtaking, train order changes, and time reserves were determined as decision variables for the management of the system after disruptions.

It can be seen that the operation process cannot be secured in terms of disruptions. Therefore, an adaptation was introduced by Foster et al. (2019), which is defined as the ability of systems to self-organize and meet the demands caused by disruptions. The approach, which explains failure mechanisms and their propagation, as well as concepts for recovery, is called Resilience Engineering (Patriarca et al., 2018).

Regarding Ouyang et al. (2019), it can be concluded that robustness is focussed on pre-event issues, while resilience is focussed on the minimization of undesirable event consequences. In resilience research, recovery from disruptions is associated with system repairs (Zhang et al., 2018), and not necessarily process management. Recovery process modelling is also the subject of diverse research works (Cassottana et al., 2019).

Resilience evaluation is focussed on disasters, large scale events, and the recovery of the system from their consequences (Hosseini et al., 2016, Rus et al., 2018, Liu and Song, 2020). Based on U.S. government documents, Zhang (2018) defines resilience as "the ability to prepare for and adapt to changing conditions and the ability to withstand and recover rapidly from disruptions". Similar to robustness research, in resilience oriented papers there is also confusion regarding these two qualities (Alipour and Shafei, 2016, Cox et al., 2011). Many contributions limit resilience to recovery until a stable system state is reached (Tang and Heinimann, 2018, Christodoulou et al., 2018). The level of system function is defined in the literature differently, and the term resilience is sometimes mixed with performance (Hosseini et al., 2016). Performance gives information about the ability of a system to implement desired tasks. It can be defined as (Knudsen et al., 2012):

- monitoring of the system,
- handling early warning deviations,
- reacting to deviations,
- learning.

The importance level of using performance indicators depends on the utilised resilience approach. Hosseini et al. (2016) identified four main groups of approaches:

- conceptual frameworks,
- semi-quantitative indices,
- structural-based models,
- general measures.

The first two categories are based on qualitative methods. Therefore, a detailed performance evaluation is not a part of that research. One of the used approaches is the qualitative Functional Resonance Analysis Method (Patriarca et al., 2018). The basic concept of evaluating performance for resilience quantification is based on the comparison of work as done with the work as imagined (Patriarca et al., 2018). Structural-based models consist of optimization, simulation, and fuzzy logic models.

Looking at (Hosseini et al., 2016, Rus et al., 2018, Liu and Song, 2020), it can be stated that about thirty percent of measures do not take into account the performance function. The remaining ones refer to average performance for a given time interval, or in a function of time, and are related to the kept performance level after disruptions. It was found that performance is described mainly in one dimension. Approaches that take into account more dimensions

tend to assess resilience separately for each of them. The relevance of quantitative resilience assessment in reference to system performance is still increasing (Xu et al., 2020).
A literature survey was made to find the most common parameters that describe the system and processes. After a general literature search, more than twenty papers connected to the investigation of resilience and performance were selected for a more detailed analysis.
Typically, only one dimension (one parameter) is taken into account for performance quantification. The most common performance parameters are:

- time (Hong et al., 2019, Lu et al., 2017, Do and Jung, 2018),
- capacity (Balal et al., 2019, Kierzkowski and Kisiel, 2017, Dessavre et al., 2016),
- number of node connections (Ouyang et al., 2015, Pitilakis et al., 2016, Ramirez-Marquez et al., 2018).

The most commonly used technique for investigating resilience with respect to performance is simulation modelling (Zou and Chen, 2019, Argyroudis et al., 2020, Jacyna et al., 2014, Ramirez-Marquez et al., 2018, Jacyna and Zak, 2016). Fuzzy logic is also used, but less often. Moreover, its utilisation is limited to general factor evaluation, and not directly to performance evaluation (Bukowski, 2016, Edjossan-Sossou et al., 2020). Research that does not focus on resilience may use fuzzy logic for evaluating performance, as was the case with Kierzkowski and Kisiel (2017).
The analysed papers deal mainly with network performance in general and are related to major events. Some papers referring to process resilience can also be found. Nevertheless, they are related to chemical processes in plants (Jain et al., 2018, Jain et al., 2019b). Moreover, finite process constraints and qualitative methods are used, making it impossible to apply the approaches in the case of the railway (Jain et al., 2019a).
To conclude the literature research, resilience is focussed on networks, and not directly on operation processes. There are no papers referring to multi parameter analysis for assessing performance. Moreover, the analysis of interdependent systems is limited to one dimensional performance functions (Zhang et al., 2018). The ordering of terms related to resilience can be seen to be the next helpful effect.

Therefore, the aim of this paper is to organize terms related to resilience and to propose a multi properties performance function for railway resilience quantification.

## 3. Resilience concepts

The basic terms related to system and process evaluation in relation to unwanted events are often mixed and used synonymously. To minimize confusion, Figure 1 shows a presentation of the most important qualities. Reliability is the ability of a system to meet requirements in a specified time interval, with no damages or failures related to the system's components (Birolini, 2017). Dependability is a wider quality. It is defined as the system's ability to perform all tasks, and to fulfil all requirements correctly in a given time interval. It means that damages to system components may occur, but the system outcome will be kept (Birolini, 2017). Both qualities make the assumption of system operation under certain conditions.

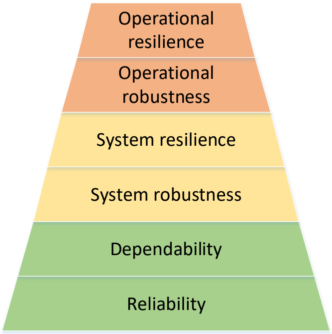


Fig. 1. Qualities describing the system in terms of unwanted events

Looking at the literature, robustness is defined as the ability to withstand shocks that influence the system (Salido et al., 2008). On the other hand, resilience is defined as the ability to recover the system in a given time period after unwanted events and their consequences (Liu and Song, 2020). As can be seen in Figure 1, this contribution proposes another approach, which divides the mentioned qualities into system and process ones. Therefore, system robustness will be defined as the ability of the system to withstand unwanted events and their consequences and to not turn into an unavailability state.

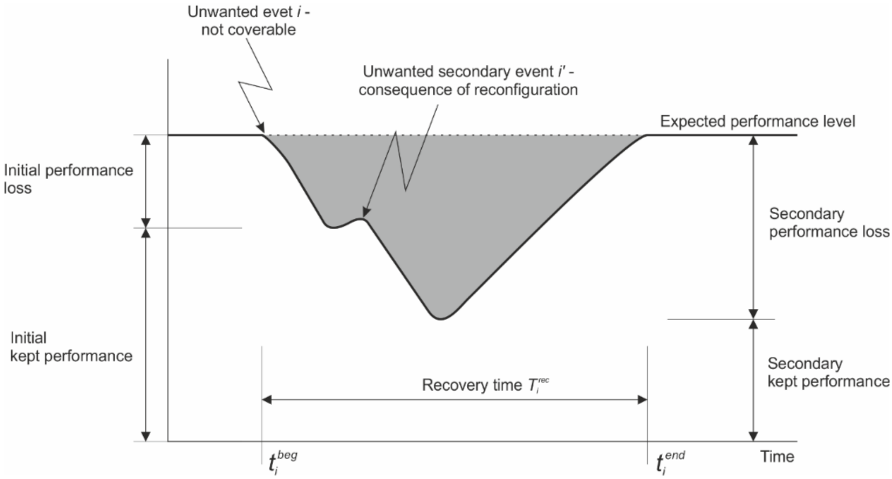

Fig. 2. Robustness and resilience concept

This is given for a specified time interval. The difference to reliability or dependability is that in the case of system robustness the conditions may change, and the operational parameters may exceed the assumed critical limits. Events that change the conditions dramatically, apart from the assumed certain ones, will be called shocks.

System resilience will be understood as the ability of the system to recover from disruptions in a given time period. It refers to major events that cause full or partial system unavailability. In this meaning, system resilience can be described using general performance measures like network capacity, available nodes etc. Operational resilience is the ability of a system to recover operation processes after they have been disrupted as a consequence of unwanted events. In terms of operational resilience, undesirable events are taken into account in terms of the outcome of the operation process. Therefore, if an unavailability situation has no influence on the operation process, it is not important in terms of operational resilience.

The recovery of operation processes can be implemented by reconfiguration actions like: the re-ordering, re-timing or re-routing of trains (D'Ariano, 2010, Corman et al., 2010, Jacyna-Golda et al., 2017a, Jacyna-Golda et al., 2017b). The literature review shows that further system consequences are not taken into account in detail for recovery actions. Nevertheless, the issue of further disruptions caused by earlier decisions is a key issue in resilience research. Figure 2 shows a concept of performance loss, recovery and further disruptions in relation to the investigation of resilience.

The information presented in Figure 2 is held on a general level. Therefore, resilience and robustness can be understood in this case as the operation and quality of the system. Performance loss, in reference to system robustness and system resilience, will not necessarily be the same as when in relation to operational variants.

## 4. Performance qualities

According to the literature review, train re-routing, re-ordering, re-timing and connection cancelling were identified as the main variables for dispatching actions. A combined fault tree and event tree analysis was performed to find out what issues would be important for the occurrence of unwanted events that are the consequence of reconfiguration actions. The main results are shown in Figure 3.

The analysis starts with not extended events. These unwanted events may be coloured black and supplemented by a number. For the first reading from the bottom to the top the numbers are not relevant. For the second reading, the numbers mean that the given situation identified in the top of the figure (where the event tree ends) may have an influence on the occurrence of the given event in the bottom of the fault tree.

The failures rise until the top event, which is named as system unavailability. It was assumed that system unavailability is each unwanted event that results in a disruption related to the operation processes. In other words, it is not necessary that there is damage to the system components. Sufficiently for the system unavailability occurrence is any event which causes delays. If the time to repair is less than the time assigned to the given operation process, than no reconfiguration is necessary and the remaining processes will be implemented without disturbances.
On the other hand, if the time margin is less than the time to repair, than there are two possibilities. Firstly, no reconfiguration actions will be implemented. If the delay is small, it can be compensated by a given number of processes in the series (train ride) without affecting other ones. Secondly, delay propagation may appear. Delay propagation in such a case is the first identified influencing factor for further delays.
If reconfiguration actions will be implemented, the final consumer can either experience consequences (transport service changes) or not (no transport service changes). For both, the implemented reconfiguration can cause further unwanted events due to:

– the reaching of limits in the train crews' working time,
– reaching limits of the vehicle interval to maintenance,
– vehicles that are inadequate for the tasks,
– inadequately prepared train crews,
– tasks outside of the daily routine.

A vicious circle may appear, and reconfigurations may lead to further disruptions, in turn making the system less stable after subsequent time steps. Therefore, a train with a schedule that is different to the expected one will be named as a reconfigured train.

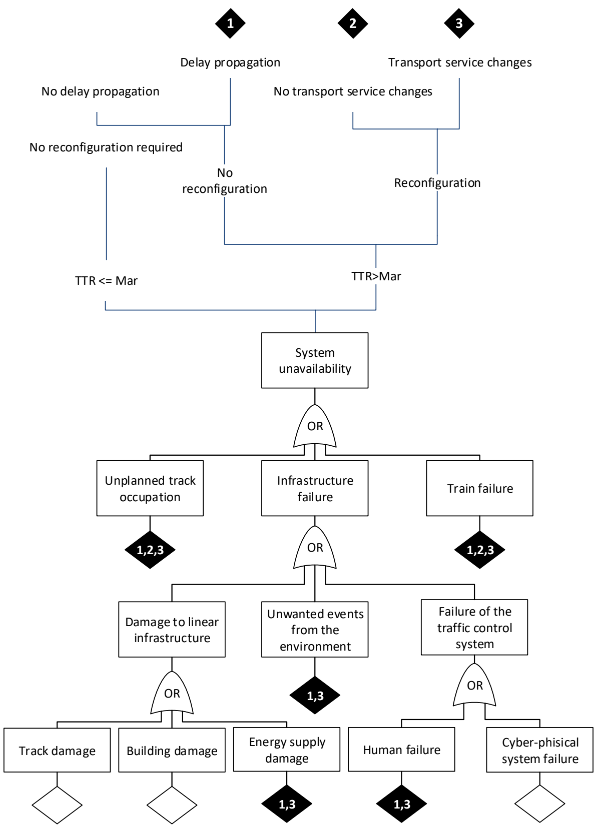


Fig. 3. The fault tree analysis combined with the event tree analysis

Reconfiguration is connected to the process of order changing, changing or cancelling of interconnections, exchanging of train crews (Golebiowski, 2020), exchanging of vehicles, and changing of tracks within a given line. It was assumed that the operation process is strictly connected to a given railway line. It follows that track changes are possible within the same railway line, with the same stops, and with the same operation points. If the railway line is changed, the scheduled process will be cancelled and a new one will be introduced into the schedule. Finally, the most useful input variables for the model were identified:

- the proportion of operation processes under implementation in opposite to cancelled ones $\theta^I$,
- the proportion of not reconfigured processes $\theta^S$,
- the proportion of punctual processes (in terms of the ending time) $\theta^P$,
- the third quartile of operation process delays $\theta^Q$,
- the ratio of the probability of no further delays for the analysed scenario to the probability of no further delays for the scheduled situation $\theta^L$, which is calculated until the end of the event.

The proportion of operation processes under implementation gives information about the operated nodes on the network. The proportion of not reconfigured processes gives information about correctly assigned train crews, vehicles and tracks (within the given railway line). The proportion of punctual operation processes and the third quartile of delays define the punctuality of the processes and the possibility of delay propagation. The probability of no further disruptions gives information about the possibility that the given solution will be robust to new random shocks.

## 5. Process description

The operation processes O of a system can be defined as:

$$O=A,D,E \quad (1)$$

where:
$A$ – set of all actions in the system, related to the operation process,
$D$ – set of all dependencies between actions,
$E$ – set of all unwanted events which impact on the system and the operational processes.

The set of actions can be described as:

$$A = \langle A^S, A^R \rangle \quad (2)$$

where:
$A^S$ – set of scheduled actions,
$A^R$ – set of additional actions, the occurrence of which is caused by reconfiguration decisions.
Actions change the state of the system e.g. the location of a train will change after the action of the train moving. This type of action, for the performed research, will be called the main operation process. There are also supporting processes. These are actions that directly allow the main operation processes to be implemented, e.g. issues related to the takeover of the vehicle by the train crew. In general, actions $a_{i|l}$ are defined in the same way for scheduled and reconfigured cases:

$$a_{i|l} = \langle c_j : c_j \epsilon C^l, t_{i|l}^{start}, t_{i|l}^{end}, \psi_m : \psi_m \epsilon \mathrm{M}^{i|l}, \gamma_n : \gamma_n \epsilon \Gamma^{i|l}, \eta_u : \eta_u \epsilon \mathrm{H}^{i|l} \rangle \quad (3)$$

where:
$c_{j|l}$ – cluster $j$ on network part $l$,
$C^l$ – subset of clusters belonging to network part $l$,
$t_{i|l}^{start}$ – starting time of action $i$ on network part $l$,
$t_{i|l}^{end}$ – ending time of action $i$ on network part $l$,
$\psi_m$ – train crew $m$,
$\Psi^{i|l}$ – subset of train crews meeting the requirements of action $i$ on network part $l$,
$\gamma_n$ – vehicle $n$,
$\Gamma^{i|l}$ – subset of vehicles meeting the requirements of action $i$ on network part $l$,
$\eta_u$ – passengers or cargo $u$,
$\mathrm{H}^{i|l}$ – subset of passengers or cargo meeting the requirements of action $i$ on network part $l$.
A cluster is a part of the railway network, and is located between two operation control points which allow the track to be changed. The cluster is described as follows:

$$c_j = \langle po_l^{start}, po_l^{end}; PO_l^{int} \rangle \quad (4)$$

where:
$po_l^{start}$ – starting point of network part $l$,
$po_l^{end}$ – ending point of network part $l$,
$PO_l^{int}$ – set of intermediate operation and commercial points on network part $l$.

The cluster, train crew, vehicle, and passengers or cargo can be treated as the resources needed to implement the required action. A supporting action may not require all the listed resources. An example of the supporting actions is the preparation of train crews for duty. An operation process can be the source of some, or all, of the listed resources to another process. Therefore, the train crew, vehicle, infrastructure, and passenger or freight interconnection will create the set of process dependencies $D$. It consists of subsets $D_{i|l}$ that are related separately to each action. A dependency can be understood as the need to finish one process in order to be able to start another one.

$$D = \langle D_{i|l} \rangle \quad (5)$$

It was assumed that a process is only dependent to one other earlier process in terms of each of the identified dependencies. Thus, a subset of dependencies for an action can consist of a maximum of four items.

$$D_{i|l} = \langle D_{i|j}^{tc}, D_{i|j}^{veh}, \ {}_*d_{i|j}^{inf}, D_{i|j}^{int} \rangle \quad (6)$$

where:
$D_{i|j}^{tc}$ - set of train crew deliveries from known actions to action $i|l$,
$D_{i|j}^{veh}$ - set of vehicle deliveries from known actions to action $i|l$,
${}_*d_{i|j}^{inf}$ - the delivery of the an infrastructure part from a known action $*$ to action $i|l$,
$D_{i|j}^{int}$ - set of passenger or freight deliveries from known actions to action $i|l$.
There were sets of train crews, vehicles and interconnections dependencies introduced because in each case may more than one process deliver members of the train crew, vehicles or passengers to the analysed action. In terms of the infrastructure, a maximum of one action must be finished until the analysed one can be started. All of these dependencies are time-related.
The last process parameter is the set of unwanted events. It can be described by subsets $E^{i|l}$ of events related to action $i|l$.

$$E = \langle E^{i|l} \rangle \quad (7)$$

Unwanted events may be related to all the resources needed to perform action $i$ on network part $l$.

## 6. Operation process evaluation model

As already stated, performance depends on a couple of issues. The identified process qualities can be characterized by the proportion of operation processes under implementation, the proportion of not reconfigured processes, the proportion of punctual processes, the third quartile of delays, the ratio of the probability of no further delays for the analysed scenario to the probability of delays within the basic schedule. These input parameters for the performance function are incoherent relative to each other. Due to different natures, they cannot be put together using the classical approach. Therefore, looking at literature examples (Kierzkowski and Kisiel, 2017, Skorupski, 2016), the fuzzy logic approach was chosen to find the performance function $f$ while taking into account the identified issues. The fuzzy set A (alpha) will be denoted as:

$$\mathrm{A} = \langle (\theta, \mu_{\mathrm{A}}(\theta)) : \theta \epsilon \Theta, \mu_{\mathrm{A}} \epsilon [0,1] \rangle \quad (8)$$

where $\mu_{\mathrm{A}}$ is the membership function of this set.
A Mamdani fuzzy inference system was constructed (Mamdani & Assilian, 1975, Zadeh, 1973), the general model of which is shown in Figure 4. For the input of the model, unfuzzy variables $\theta$, estimated depending on the type of variable, are used. During the input fuzzification, the sharp variables are connected to linguistic variables.

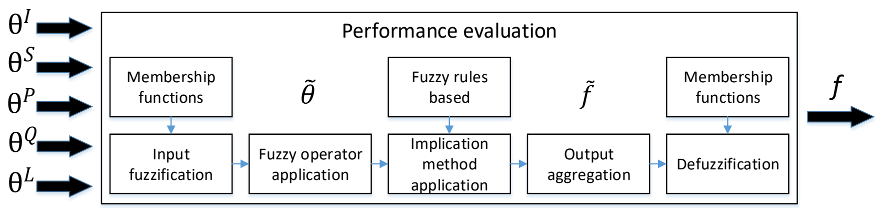


Fig. 4. Concept of the performance evaluation model.

The fuzzified values $\tilde{\theta}$ are then input for applying the implication method, which uses the set of fuzzy rules and prerequisites to estimate the linguistic variable $\tilde{f}$. It is finally transformed during the deffuzification process to the outcome in form of the performance function $f$.
When applying the implication method, AND and OR operators are used. For the AND operator, a min(*) function is used, while for the OR operator, the maximum function max(*) is used.
For the input variables $\theta$ and the output variable $\tilde{f}$, membership functions were established. The function shapes are shown in Figures 5 and 6. The membership functions were elaborated in cooperation with experts from the railway industry and by using the two literature reviews performed by Restel in 2014 and 2019.
The third quartile of delays $\theta^Q$ (Figure 5a) is characterized by the linguistic variables *Good* and *Poor*. The input variable's $\theta^Q$ domain starts at zero and is not limited to the right side. The value is calculated for the process data, taking into account only the non-zero delays.
According to the literature survey shown in (Restel, 2014), the acceptable delay level varies from 2.5 minutes up to 5 minutes. A delay between 5 and 15 minutes can sometimes be accepted, but delays higher than 20 minutes are not acceptable.
The proportion $\theta^L$ of no further delays for the actual situation related to the scheduled situation is calculated using the following formula:

$$\theta^L = \frac{\prod_{c=1}^{d}(1 - P_c^{act})}{\prod_{c=1}^{d}(1 - P_c^{sch})} \tag{9}$$

where:
$c$ - the given pair of dependent processes,
$d$ - number of dependent process pairs until the end of the disruption,
$P_c^{sch}$ - probability of disruption propagation for process pair $c$ according to the theoretical schedule,
$P_c^{act}$ - probability of disruption propagation for process pair $c$ according to the actual schedule.
The input variable $\theta^L$ is characterized by the linguistic variables *Good* and *Poor*. Its lower domain border is zero, while its upper border is theoretically not limited. Nevertheless, the possibility that a new-made schedule would be better than the theoretical one is quiet low. Therefore, the expected values should be lower than one. The concept of such disruption propagation probability quantification was explained by Friedrich et al. (2019).
The proportion of scheduled processes under implementation $\theta^I$ (Figure 5c) is characterized on its domain [0,1] by the variables *Good* and *Poor*. The proportion of punctual processes $\theta^P$ (Figure 5e), as well as the proportion of not reconfigured processes $\theta^S$ (Figure 5d), are both described by three linguistic variables on their domains [0,1]. Additionally to *Good* and *Poor*, the variable *Intermediate* has also been introduced.
The output variable performance was settled by a range from zero to one. One means that there are no disruptions, and that the system is operated within the schedule. For the output variable, nine membership functions were established (Figure 6).
For applying the implication method, fifty nine rules were established. There is no difference in the weight of the rules. For all rules, according to the input membership functions, the output membership function values are calculated as $\mu_{out}^{R1}(z), \mu_{out}^{R2}(z), \dots, \mu_{out}^{R59}(z)$. During the implication step, the minimum function value was used, while during the output aggregation, the maximum function was used.
Finally, the defuzzification process is implemented based on the centroid estimation.

$$z^* = \frac{\int \mu_{out}(z) \cdot z dz}{\int \mu_{out}(z) dz} \tag{10}$$

The described performance evaluation model was implemented in MATLAB software.

## 7. Case study

Figure 7 shows a theoretical, graphical timetable for an existing railway line in Poland. It is double tracked. There are express trains marked in red, and black regional trains and freight trains marked in grey. There are some branches to other lines, where trains enter or leave the analysed line, but there is no possibility to reroute the trains, except on the neighbouring track.
It was assumed that damage occurred on one of the tracks between nodes B and C at 19:35, which lasted for two hours (marked as a violet arrow). The simplest dispatching strategy was implemented – the train order was not changed, and all trains moved one after the other on the available track. For each

minute, the number of processes (train moving on the track) in the system, the number of delayed processes, the number of reconfigured processes (moving on the wrong track), the delays, and the remaining dependencies (until the end of disruption) were estimated. Using the data, the input variable values were calculated.

It was found, that for all trains the delay probability distributions on the analysed sections are quiet similar. The sections belong to the Lower Silesian railway network, but cannot be named directly due to a confidentiality agreement. The punctual arrival probability is about 0.949. The remaining 0.051 can be described by the lognormal distribution LN(2.2552;0.8783), as shown in Figure 8. It was estimated for this railway line basing on operational data from the Polish Infrastructure Manager from the years 2009-2011. More than six hundred unwanted events have been registered, that influenced 1208 from 23686 analysed train rides. The distribution parameters were proven by Chi-squared test at significance level 0.05.

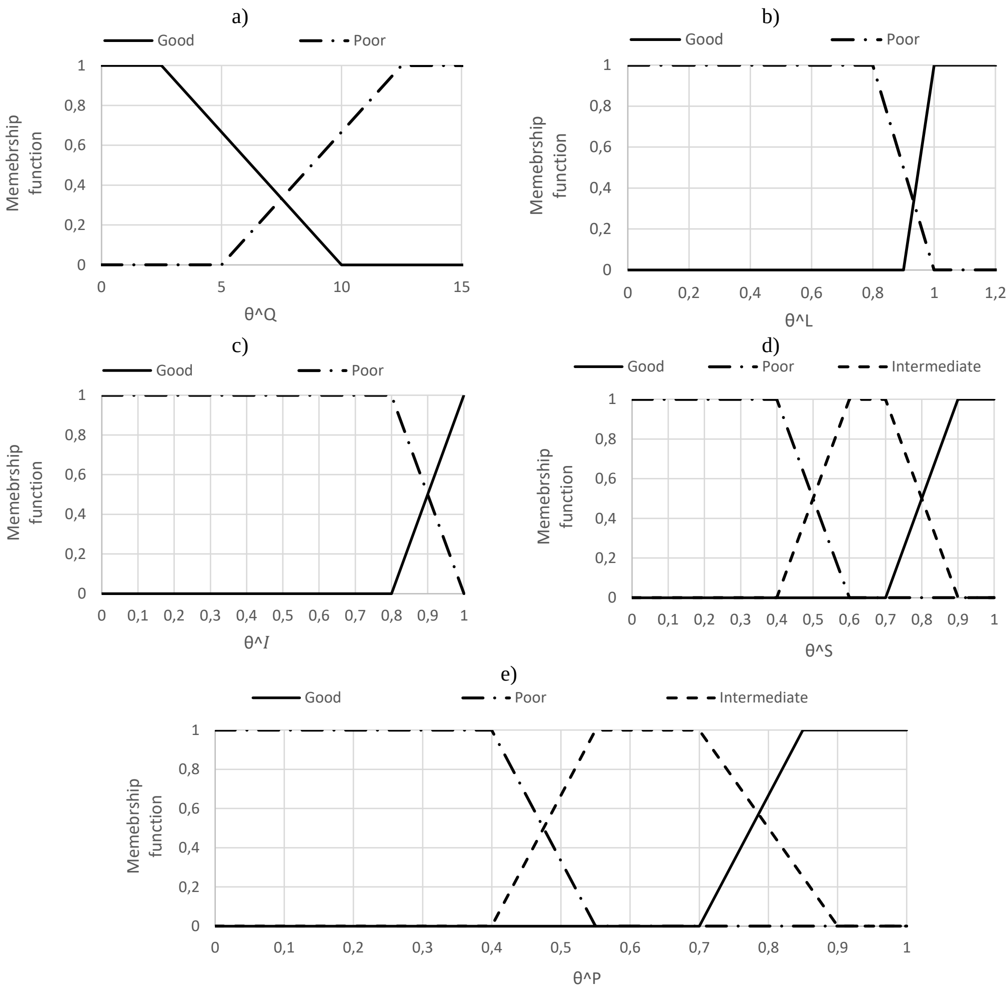


Fig. 5. Membership functions for the input and linguistic variables: a) third quartile of delays, b) ratio of the probability of no further scheduled/actual delay , c) proportion of processes under implementation, d) proportion of no reconfigured processes, e) proportion of punctual implemented processes.

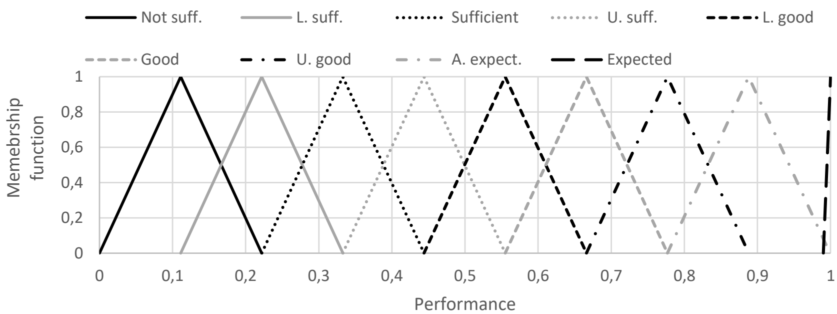


Figure 6. Membership functions for the output variable and linguistic variables.

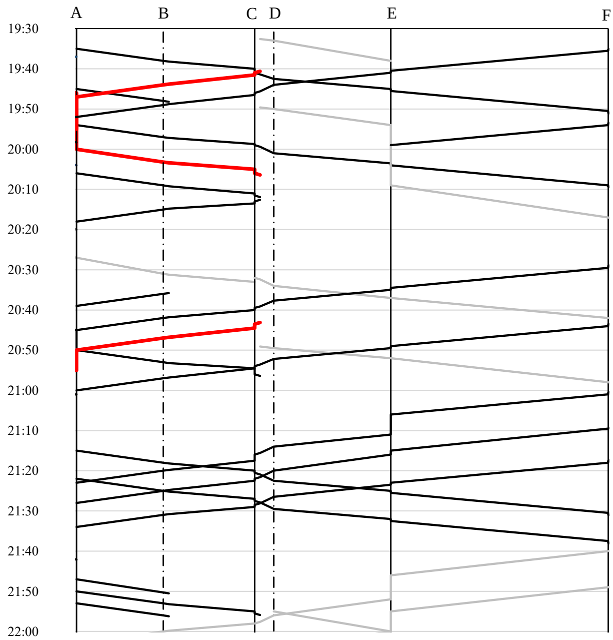


Fig. 7. Example of an operation situation related to a real timetable.

All input variables were paired with the time axis. Using the database, the fuzzy operation performance function was computed in Matlab software. The results are shown in Figure 9.

Additionally to the performance curve, two individual performance measures that were used in the literature were also presented – the proportion of delayed and the proportion of available node connections in the analysed system.

As can be seen, the node connections indicator is static, and not related to the performed processes. Close to that will be all indicators related to maximum flow capacity. Thus, such parameters are not good enough for a system like the railway, because dynamical process issues are not taken into account. On the other hand, taking only one dynamical indicator, such as the proportion of delayed processes, will be strong and the gathered perception of the situation will be distorted.

It can also be seen that both the dynamical and static issues are covered by the proposed approach, and it can therefore be seen to be a new promising tool for evaluating operation processes.

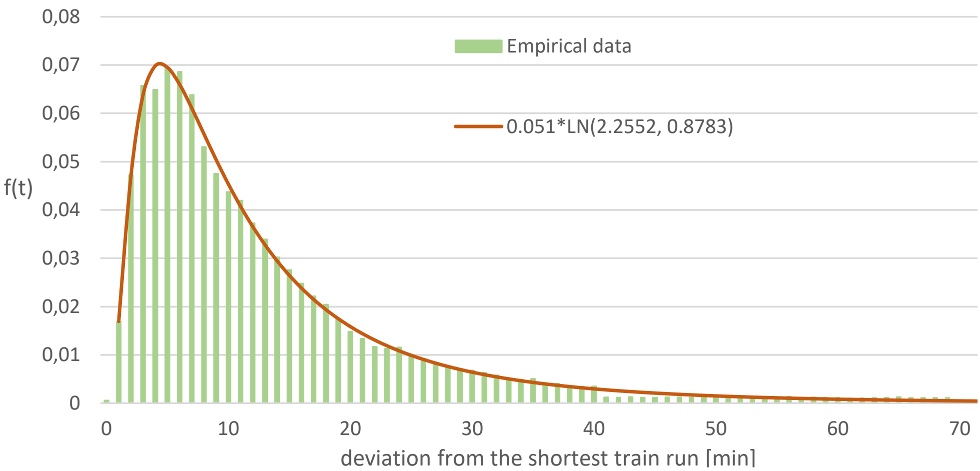


Fig. 8. Probability distribution of time deviations from the shortest train run for a chosen Polish railway line.

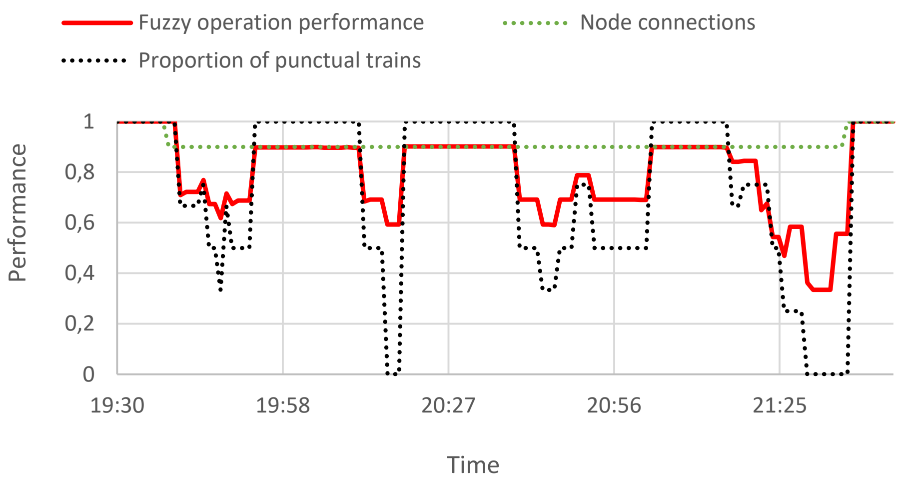


Fig. 9. Performance evaluation for disrupted railway operation processes.

## 8. Conclusions

The introduced concept of operational resilience and operational robustness allows the ordering of issues related to system reliability, robustness and resilience research. It opens a new view on evaluating the system after unwanted events, especially in terms of complex socio-technical systems with operational process dependencies. The proposed concept makes it possible to perform a more structured evaluation of systems and processes. Thus, recovery after unwanted events will be more efficient and the safety of the system will increase.

Secondly, as a result of this research, operational issues influencing the occurrence of failure were identified. It was found that the recovery process can initiate further unwanted events, and therefore destabilize the operation processes. Therefore, particular attention must be paid to process dependencies, which were identified as vehicle and train crew rotations, track occupation, and the interconnections of passengers or freight.

The incoherent process parameters could hardly be put together for one multi criterial approach. For this reason, the fuzzy approach, taking into account these

parameters, was used to identify the performance curve . The elaborated fuzzy model is based on the knowledge of collected literature, expert knowledge, and the performed operational research. The method allows the typical resilience problem to be combined with the typical dispatching problem. According to the case study, it can be seen that the fuzzy model includes both approaches. The results are promising and further research is planned.
For the future it is assumed that the introduced operational variants of resilience and robustness will be investigated more deeply. Moreover, their quantification, based on actual results, will also be performed. Finally, optimization issues will be taken into account to support the planning and implementing phases of operational schedules.

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# STUDY OF THE POSSIBILITY OF USING TRANSMISSION IN THE LTE SYSTEM ON A SELECTED RAILWAY LINE FOR THE PURPOSE OF RUNNING RAILWAY TRAFFIC

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## *Abstract:*

*The railway and the Rail Traffic Control Systems installed on it in Poland have recently experienced rapid technological development. This is undoubtedly due to the funds that Poland receives from the European Union for the modernization of railway infrastructure. The development of modern railway infrastructure means not only stations, modern rolling stock, but also safe and reliable train control systems based on the latest telecommunications and information technologies. For a longer time, radio communication based on the GSM-R (GSM for Railways) standard is being introduced on PKP. For this purpose, dedicated infrastructure is being built in order to use this technology for railway traffic. This is associated with huge investment costs. Since the beginning of its existence, research has been conducted worldwide on the use of LTE (Long Term Evolution) technology for conducting railway traffic. For economic and technological reasons, it is necessary to study other possibilities of using modern telecommunications infrastructure not yet dedicated to railway tasks in these open networks. The article will present research on the use of open radio communication network based on LTE standard for rail traffic and passenger comfort. It will discuss the research method and selected results of measurements made on railway line no. 4. The choice of this railway line was dictated by two factors. The first one resulted from the maximum train speed, the second one is the variety of rolling stock used on this line (compartmental and non-compartmental wagons). The part of research concerning collection of measurement material was performed within the framework of completed research work PBS3/A6/29/2015. As a result of conducted in-depth literature analysis as well as performed measurements and calculations, it allowed to develop a model and software for simulating system operation in real conditions. This system allows to send railway telegrams on appropriate safety level defined in standardization documents. The research proved the possibility of using an open system in the LTE standard for the transmission of signals for railway traffic control and passengers while maintaining an appropriate level of safety. The only limitations which were indicated by the tests are improper radio interface coverage of railway lines. Appropriate planning of radio coverage of railway areas by radio communication operators (so far ignored) with proper cooperation of infrastructure manager can lead to launching efficient communication system without necessity to build specialized infrastructure for railway.*

***Keywords:*** *GSM-R, LTE, open systems, traffic control*

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## 1. Introduction

The introduction of microprocessor technology into the railway traffic control equipment took place at the turn of the century. However, the use of modern radio systems in rail transport is the moment when standard-based technology appeared in the world. GSM (Global System for Mobile Communications). For the needs of railways, and in particular aspects related to railway traffic control, this technology has been extended by giving it its name to the GSM-R standard. Unlike the GSM version, the frequency band in which the railway system operates has been extended and information transmission in two channels each 4 MHz wide has been introduced. FM (Frequency Modulation) systems currently used on the railways in Poland did not allow for data transmission due to their specific nature of modulation. However, some aspects of "data transmission" were used in radio-stop system. GSM-R transmission enables not only transmission in relation track - vehicle but also in relation track - track. Therefore, it has also become the basis for using it for remote wireless management of railway infrastructure.

Due to the degradation of wired infrastructure connecting the element of railway control systems, and related primarily to their destruction, the use of radio transmission medium for independent management of railway traffic control equipment is increasingly considered. An unquestionable problem when implying such solutions is the safety of transmission in such systems. It should be emphasized that safety at a certain level of transmission is already offered by the radio transmission systems themselves, which was also used in the GSM-R standard. Creation of a separate system for the needs of railways is connected with huge expenditures on designing, testing, certification and finally building and implementing such technology. Therefore, it is possible to use public open radio networks for railways, which will reduce costs because such a system relies on existing infrastructure.

A means of transmitting information that meets the requirements for safe transmission in the sense of railway traffic control systems should be developed. Therefore, a model for open radio transmission in public traffic control systems based on the public radio standard, LTE, will be presented later in this article.

The research methodology and assumptions will be presented. A measurement system will also be presented, which was used for actual measurements on the railway line based on the developed data transmission method. The obtained selected measurement results are original, as no research on the use of open data transmission for railway purposes using the LTE system has been conducted worldwide.

## 2. Literature review

Theoretical and practical aspects of srk systems (i.e. railway traffic control systems), including solutions applied in Poland, are presented in works (Brodzik 2019; Ciszewski et al., 2017; Jacyna et al., 2018; Mikulski and Gorzelak 2017; Zboiński and Woźnica 2010; Toruń et al., 2019; Burdzik et al., 2017, Kycko et al., 2018). This work does not, however, include solutions based on open data transmission systems.

Theoretical analysis and modelling of broadband signals, including in the LTE system, for various application areas has been presented in publications (Brazeetta et al., 2016; Baek et al., 2014; Chou et al., 2016; Gao et al., 2010, Nguyen et al., 2016).

Broadband signal propagation and related issues have been widely discussed, but no consideration has been given to rail issues under these headings.

The methodology of research as well as results and analyses of computer simulations concerning mathematical modelling of the system and transmission channel, paying attention to ensuring adequate capacity and reliability of the system and taking into account the problem of train movement were described in (Chrzan, 2018; Chrzan, 2020, Chen et al., 2017; Joshi et al., 2017, Kukulski et al., 2019).

The LTE system architecture and issues related to broadband signal transmission have been standardized in (3GPP, 2020).

The possibility of use in railway systems was not indicated there, however.

Due to the specificity of access to the technology and frequency bands used, the solutions presented above are based on the analysis of electromagnetic compatibility of existing radio systems based on frequencies specific for given regions (800, 900, 1800, 2100, 2500 MHz) (Chrzan, 2018; Chrzan, 2020). In this work, however, the consideration will concern the bands available for Polish users in railway radio communication.

Extremely important for the analysis of LTE system operation, not only in railway applications, are issues related to the use of modern antenna systems based on adaptive antenna technology, the use of SDMA (Space Division Multiple Access) or MIMO (multi-antenna systems) (Kamel et al., 2014; Parichehreh et al., 2016; Toruń et al., 2019; Bohagen et al.,2005, González-Coma et al., 2020; Hu et al., 2019).

Currently, there are no studies conducted in Poland aimed at using the LTE system on railways as a natural successor to the European system of railway radio communication based on the GSM-R standard, currently being introduced in our country. Within the framework of research works carried out at the WTEiI (Faculty of Transport, Electrical and Information Technology of the University of Technology and Humanities in Radom), an attempt was made to develop a method of safe data transmission between railway traffic control devices using fourth generation radio systems. These tests were limited to signal transmission in relation between the equipment installed on the track and LCS. However, there are no concepts and solutions for signal transmission in the track-vehicle relationship (Chrzan, 2018; Chrzan, 2020)

## 3. Analyses - case studies

### 3.1. Modelling the transmission system in a track-to-train relationship

The following assumptions were made for modelling the system of open radio transmission of telegrams between the traffic control devices and the Local Control Centre at WTEiI:

- the system includes traffic control devices with specific functionality and characteristics,
- srk devices have operating approvals and have safety certificates at a specific SIL (Safety Integrity Level) (Ciszewski et al., 2017; Idirin et al., 2011),
- radio transmission changes the transmission medium from wired to wireless, which means that the behavior of these devices should not change - their parameters are determined,
- radio transmission takes place under LOS (Line of Sight) and NLOS (Non-line-of-sight) conditions resulting from the specificity of the site,
- radio transmission takes place in open systems,
- the network load is a natural load, no influence on the network traffic generated by the measuring system - actual conditions in which the system is to operate,
- for modelling purposes, we assume the GSM-R transmission parameters with the assumption that meeting these conditions meets the transmission security conditions (Siergiejczyk and Rosiński, 2019).

### 3.2. The transmission model and the measurement method

In order to make measurements in the physical environment, a transmission model was built for an open system based on LTE transmission. The system in which the transmission takes place in the first stage of tests between virtual software LCS (Local Control Centre) and virtual control device, located on the train path. Within the framework of measurements, a system which is not a real time system from the Microsoft Windows operating system family was used. As a field transmitting device, a computer with Microsoft Windows 10 professional system was used along with MOXA OnCell G3470A-LTE modem (with parameters below) equipped with MIMO antenna systems (Multiple Input, Multiple Output) (Kamel et al., 2014; Parichehreh et al., 2016; Toruń et al., 2019; Bohagen et al.,2005, González-Coma et al., 2020; Hu et al., 2019).

On the receiving side there was a Windows 10 professional computer connected to the Internet via a broadband LTE network via a gateway (Fig. 1) with the following parameters (Chrzan, 2020):

- supported standards: GSM/GPRS/EDGE/LTE/ /UMTS/HSPA;
- transmission bands: LTE 2100/1800/2600/900/ /800 MHz (B1/B3/B7/B8/B20);
- UMTS/HSPA 2100/1900/850/800/900 MHz;
- transmission speed: LTE - 20 MHz bandwidth: 100 Mbps DL, 50 Mbps UL;
- HSPA - 42 Mbps DL, 5.76 Mbps UL;
- EDGE - 237 kbps DL, 237 kbps UL;
- GPRS - 85.6 kbps DL; 42.8 kbps UL;
- 4 LAN interface ports RJ-45 10/100/1000Mbps;
- cellular network antenna connectors: 2, SMA (female);
- console port: RS-232 (RJ-45);

- network protocols: ICMP, DDNS, TCP/IP, UDP, DHCP, DNS, SNMP, HTTP, HTTPS, SMTP, SNTP, ARP;
- routing/firewall: NAT, forwarding port, IP/MAC/Port filtering;
- VPN: maximum number of tunnels - 5, IPSec (DES, 3DES, AES, MD5, SHA-1, DH2, DH5), PSK/X.509/RSA;
- configuration and management options: SNMP v1/v2c/v3, Web / Serial Console, SSH, Remote SMS Control;
- number of SIM cards: 2.

The computer with the MOXA gateway served as the Local Control Center (LCS) located in the Department of Transport, Electrical Engineering and Computer Science in Radom.
The measurements were made on the railway line Warszawa Centralna - Kraków Główny running on the railway line no. 4 - Central Railway Main Line.
In order to send information, the methodology of the telegram creation and its transmission is the same as the standard for the transmission in open systems PN-EN50159:2011.
Fig.2 presents block diagram for the algorithm used to transmit datagrams.

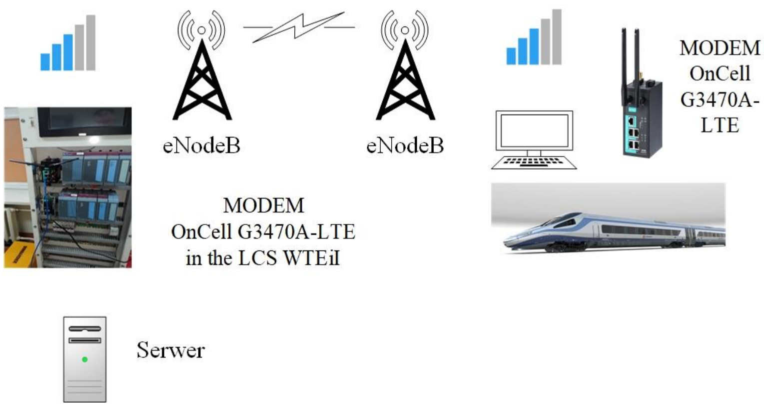



Fig. 1. Measuring system

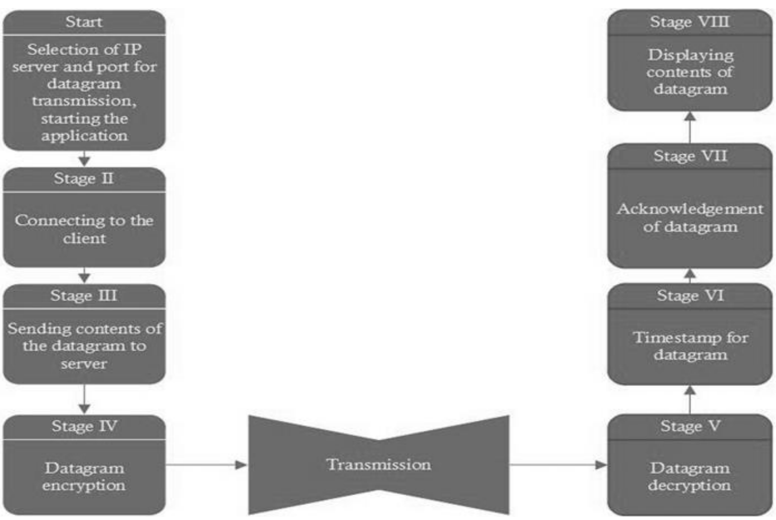



Fig. 2. The block diagram for algorithm used to transmit datagrams (Chrzan, 2018)

According to safety requirements, presented system should take into account following aspects (Chrzan, 2018):

– datagram numbering, it prevents the system from unintentional (intentional) deletion of datagram or datagram resequencing. Additionally, it allows for verification of order in which datagram arrives;
– Cyclic Redundancy Check (CRC) is used to verify plausibility and integrity of transmitting datagram. This method allows for single error detection based on the comparison of checksum appended to datagram with checksum which is calculated for datagram after receiving its contents. It should be noticed that CRC algorithm has been already embedded in Quality of Service (QoS) layer of LTE technology. In addition to that, Hybrid Automatic Repeat Request (HARQ) layer and Adaptive Modulation and Coding (AMC) layer are also responsible for correct transmission in difficult propagation conditions. Therefore, it seems to be reasonable to remove one CRC algorithm from LTE transmission. This removal allows for a decrease in datagram transmission delay and does not have the influence on safety of transmission specified in PN EN 50159:2011 standard;
– Maximum period of time in which the receiver waits for system response. It decreases datagram transmission delays;
– Advanced Encryption Standard (AES) algorithm has been used to prevent datagram transmission from hacker attacks. In the author's opinion this algorithm is sufficient for present and future systems.
– Solutions occurring in closed systems specified in EN 50128:2011, PN EN 50129:2019-01 and PN-EN 50159:2011 were adapted for open systems by authors. It results from the assumption that open systems should ensure at least the same Safety Integrity Level (SIL) as closed systems (Chrzan, 2020; Idirin et al., 2011).
– Overall system safety results from the safety of its elements. Because railway traffic control systems have a direct impact on the traffic safety, therefore they have to meet tough SIL-4 level for which, according to IEC 61508-1 norm, Tolerable Hazard Rate (THR) varies in the range of <10-9; 10-8).
– Due to impossibility of integration of presented solution with actual railway traffic control systems at this stage of research, only safety of radio communication interface has been analyzed.
– Radio communication interface under analysis uses LTE public network, what corresponds to project assumptions. Because LTE is an open system, research was conducted for actual transmission parameters and unknown system load. In authors opinion, such approach allows for plausible assessment of usefulness of system in tasks concerning railway traffic control. It results from the fact that indeterminist load of the network in fixed time interval allows us to determine actual delays and correctness of transmission. Such approach is necessary to assess the lowest possible value for parameters which should be guaranteed to ensure assumed Safety Integrity Level.
– According to PN-EN 50159:2011 standard, proposed system belongs to SIL-3 layer. Specification for SIL-3 also enumerates transmission in GSM-R, GPRS and Wi-Fi (802.11) standards. LTE technology uses packet transmission and has built-in "responsibility" for transmission correction so that LTE can be regarded as single channel transmission for which THR varies in the rage of <10-9; 10-8). Therefore, in authors opinion, proposed system based on LTE technology satisfies SIL-4 standard requirements (Toruń et al., 2019).

The measurement was based on sending an encrypted message from the device simulating the srk device installed on the line to the local control centre. Random messages were transmitted in sizes 16B, 32B, 64B, 128B, 256B, 512B, 1024B, 2048B, 4096B, 6144B, 8192B and 10240B. The measurements were related to the delay of message transmission in a set period of time, which was 900 s. The total time needed to transmit a message consisted of such factors as: time of encoding the message, time of transmitting the message through the cellular network and time of decoding the message.

The following algorithms were used to encrypt random railway messages of different sizes:

– AES CBC (Advanced Encryption Standard – Cipher Block Chaining)
– AES ECB (Advanced Encryption Standard – Electronic Codebook)

- DES CBC (Data Encryption Standard – Cipher Block Chaining)
- DES ECB (Data Encryption Standard – Electronic Codebook)
- RSA (Rivest–Shamir–Adleman) o długości klucza 1024 i 2048 bitów

The designed measuring program includes two modules: Server (being an LCS simulator) - and Client (being a transmission receiver). The Server program allows to connect with the Client program after establishing common transmission parameters such as: IP address, TCP protocol port number, and determining the method of the signal encoding. In case of RSA transmission with the use of a key - the server program allows to generate the key on the basis of the entered password. The server program receives the transmitted telegram, decrypts it, checks its integrity and sends the receipt confirmation to the Client. The program which initiates the exchange of transmission with a specific data encryption is the Client's program. Additionally, it enables sending a fixed message (telegram) of a specified length cyclically, at a specified time, sending a variable message, generated separately to each connection with the server, of a fixed length, generated cyclically, at a specified time, sending a single message of a specified length.

The telegram sent from the client to the server is constructed in such a way as to meet the safety requirements for open and closed transmission systems contained in the PN-EN50159:2011 standard, which is related to the used hardware and software working on it. Ensuring an appropriate safety level of telegram transmission should be carried out in a way that enables detection of signal transmission errors from the sender to the recipient, and in case of transmission interruption above a specified time, the system should cause a transition to a state ensuring safety. The results were saved to a file in excel spreadsheet format Fig. 3.

Because of the high non-stationarity of the propagation medium, which is the LTE system, a single measurement result is unreliable or repeatable. In such a case, the measurements were classified in terms of the probability of exceeding a certain delay of the received signal. The value of this probability is in the range 1-99%, however, typical values of this parameter are: 1%, 10%, 50%, 90% and 99%. For the purpose of the study, which is the study of delays, medians were used, i.e. middle values of an ordered subset of measurement results, whose probability of exceeding by other results from this subset is 50% (Brazeetta et al., 2016). In practice it is connected with determining the median $P_{OP}^{i}$ value of the measurement signal delay at the receiver's input for the *i*-th subset of measurement data, created from *n* measurement results, collected on the route with the length of 40 λ according to the relation below:

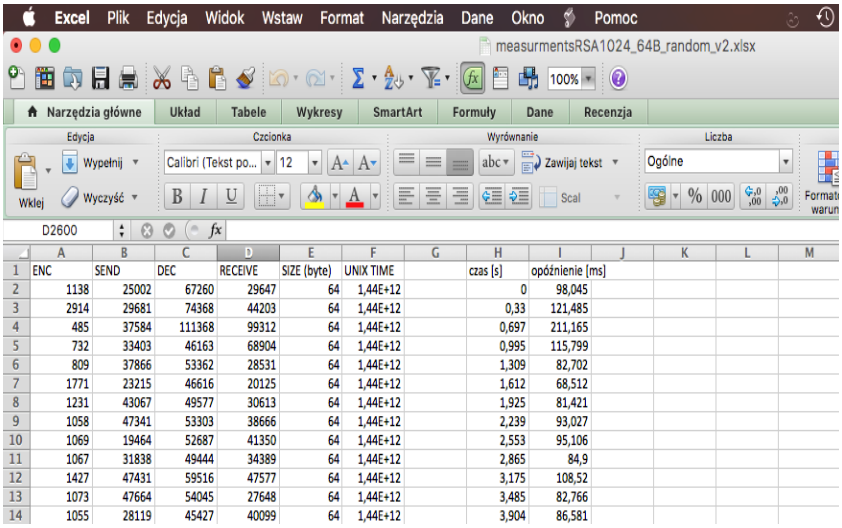
$$P_{OP}^{i} = \begin{cases} P_{OP,\frac{n+1}{2}}^{i} & ,for\ not\ even \\ \frac{1}{2}\left(P_{OP,\frac{n}{2}}^{i} + P_{OP,\frac{n}{2}+1}^{i}\right) & ,for\ n\ even \end{cases} \tag{1}$$

is an orderly subset of *n* of signal delay measurement results at the receiver's input and *n* is the number of measurements taken on the *i*-th (*i*=1,2,3... ) section of the propagation path tested.

The process of median determination was carried out in real time, during the measurement tests on the section of the railway line No 4, but according to the designed algorithm of the program described in Figure 2 only determined median values of the measured signal are recorded. The designed program also allows to record all the results at specific measurement points and to determine the median values after the tests (excel sheet). The results obtained with the use of both methods can be used to model the attenuation of the tested propagation environment and signal arrival delay on selected sections of railway line No. 4.

On the basis of the algorithm presented above and relation (1), all files with the results of field tests were integrated into one and data concerning the suspension height of transmitting and receiving antennas, frequency of the tested signal and observation data concerning propagation conditions prevailing on the Central Rail Line during particular measurement series were supplemented.

Using the knowledge of characteristic points' coordinates (geographical coordinates of the position of traffic control devices) and the commonly known relation to the value of the angle between two straights on the plane, the angle of radio waves' arrival to the receiver in relation to the axis of the main communication line was calculated for each propagation case.




| | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| 1 | ENC | SEND | DEC | RECEIVE | SIZE (byte) | UNIX TIME | | czas [s] | opóźnienie [ms] |
| 2 | 1138 | 25002 | 67260 | 29647 | 64 | 1,44E+12 | | 0 | 98,045 |
| 3 | 2914 | 29681 | 74368 | 44203 | 64 | 1,44E+12 | | 0,33 | 121,485 |
| 4 | 485 | 37584 | 111368 | 99312 | 64 | 1,44E+12 | | 0,697 | 211,165 |
| 5 | 732 | 33403 | 46163 | 68904 | 64 | 1,44E+12 | | 0,995 | 115,799 |
| 6 | 809 | 37866 | 53362 | 28531 | 64 | 1,44E+12 | | 1,309 | 82,702 |
| 7 | 1771 | 23215 | 46616 | 20125 | 64 | 1,44E+12 | | 1,612 | 68,512 |
| 8 | 1231 | 43067 | 49577 | 30613 | 64 | 1,44E+12 | | 1,925 | 81,421 |
| 9 | 1058 | 47341 | 53303 | 38666 | 64 | 1,44E+12 | | 2,239 | 93,027 |
| 10 | 1069 | 19464 | 52687 | 41350 | 64 | 1,44E+12 | | 2,553 | 95,106 |
| 11 | 1067 | 31838 | 49444 | 34389 | 64 | 1,44E+12 | | 2,865 | 84,9 |
| 12 | 1427 | 47431 | 59516 | 47577 | 64 | 1,44E+12 | | 3,175 | 108,52 |
| 13 | 1073 | 47664 | 54045 | 27648 | 64 | 1,44E+12 | | 3,485 | 82,766 |
| 14 | 1055 | 28119 | 45427 | 40099 | 64 | 1,44E+12 | | 3,904 | 86,581 |

Fig. 3. Recording of telegram data communication parameters

In the next part it has been assumed that the same transmitting and receiving modems are used, the transmitting antennas are in a radio channel with the same parameters, so it can be assumed that the resulting antenna disappearances are correlated. For transmitting and receiving devices *m* correlated distribution of Rice'a in antenna *n* can be expressed as a relation:

$$h_{nm}(t) = \sqrt{\frac{K_m}{1+K_m}}e^{j\theta_{nm}} + \sqrt{\frac{K_m}{1+K_m}}b_{nm}(t) \qquad (2)$$

where $K_m$ parameter *K* Rice'a the physical channel from the base station to srk *m* devices, and the angle $\theta_{nm}$ assumed in formula (2) is determined as follows (Baek et al., 2014; Chou et al., 2016):

$$\theta_{nm} = \frac{2\pi d f_c \cos\Theta_m}{c} \qquad (3)$$

where the distance d between two antenna elements is no more than the wavelength, $\Theta_m$ means the angle between the direct signal path and the position on the railway line of the srk equipment.

In equation (2), the component $\sqrt{\frac{K_m}{1+K_m}}b_{nm}(t)$ is modelled by $b_{nm}(t)$, which is an independent composite random variable of Gauss with zero expected value and variance of 1: $b_{nm} \sim CN(0,1)$.

In the case of a railway communication, it should be assumed that the DOA (degree of arrival) depends on the position of the srk equipment relative to the eNodeB base station and can be designated as (Nguyen et al., 2016):

$$\Theta_m = \begin{cases} arctg\left(\frac{\sqrt{R^2-d_{min}^2}-d_m}{d_{min}}\right), \\ \quad if: 0 \le d_m \le \sqrt{R^2-d_{min}^2} \\ \pi - arctg\left(\frac{d_m-\sqrt{R^2-d_{min}^2}}{d_{min}}\right), \\ \quad if: \sqrt{R^2-d_{min}^2} < d_m \le 2\sqrt{R^2-d_{min}^2} \end{cases} \qquad (4)$$

where $d_m$ is the distance to the transmitting and receiving equipment.

When exchanging information in the LTE system between the base station and the srk devices in the field in time slot *t* the same block of data symbols $x(t)$ is multiplied by the composite number $\sqrt{\alpha_n(t)}exp(j\phi_n(t))$ in the *n*-antenna and broadcast, as appropriate, from all the antennas, for $n = 1,\ldots,$ N tak, że $\sum_{n=1}^{N}\alpha_n(t) = 1$ while maintaining total transmitting power. The received signal model from all $N_t$ transmitting antennas to the transmitter-receiver m is described by the relation:

$$y_m(t) = \\ = \left(\sum_{n=1}^{N_t} \sqrt{\alpha_n(t)} exp\left(j\phi_n(t)\right) h_{nm}(t)\right) x(t) \\ + \eta_m(t) \quad (5)$$

where $\eta_m(t)$ is Gauss's additive white noise in $\eta_m(t) \sim CN(0, \sigma^2 I_T)$.
Therefore, the overall channel gain for transmitter-receiver *m* is:

$$\tilde{h}_m(t) = \sum_{n=1}^{N_t} \sqrt{\alpha_n(t)} exp\left(j\phi_n(t)\right) h_{nm}(t) \quad (6)$$

For a correlated distribution of the Rice'a channel, dependency (6) can be transformed further as:

$$\tilde{h}_m(t) = \sum_{n=1}^{N_t} \sqrt{\alpha_n(t)} exp\left(j\phi_n(t)\right) h_{nm}(t) = \\ = \sum_{n=1}^{N_t} \sqrt{\alpha_n(t)} exp\left(j\phi_n(t)\right) \cdot \\ \cdot \left(\sqrt{\frac{K_m}{1+K_m}} exp(j\theta_{nm}) + \sqrt{\frac{1}{1+K_m}} b_{nm}(t)\right) = \\ = \sqrt{\frac{K_k}{1+K_k}} \sum_{n=1}^{N_t} \sqrt{\alpha_n(t)} exp\left(j(\phi_n(t) + \theta_{nm})\right) + \\ + \sqrt{\frac{1}{1+K_k}} \sum_{n=1}^{N_t} \sqrt{\alpha_n(t)} exp\left(j\phi_n(t)\right) b_{nm}(t) \quad (7)$$

For $B_m(t) = \sqrt{\frac{1}{1+K_m}} \sum_{n=1}^{N} \sqrt{\alpha_n(t)}\, exp\left(j\phi_n(t)\right) b_{nm}(t)$ then it can be shown that $B_m(t)$ is the Gauss combined random variable from $B_k(t) \sim CN(0, \sigma_m^2)$, where $\sigma_m^2 = \frac{1}{1+K_m}$. Let $H_m(t)$ is the amplitude $\tilde{h}_m(t)$:

$$H_m(t) = \left|\tilde{h}_m(t)\right| = \\ = \left|\sqrt{\frac{K_m}{1+K_m}} \sum_{n=1}^{N_t} \sqrt{\alpha_n(t)} exp\left(j(\phi_n(t) + \theta_{nm})\right) + \\ + B_m(t)\right| \quad (8)$$

In accordance with (Baek et al., 2014; Chou et al., 2016) $\sqrt{\alpha_n(t)} = \frac{1}{\sqrt{N}}$ and in combination with relation (3) to maximize the size of the entire channel, a phase can be defined as:

$$\phi_n(t) = -\frac{2\pi n d f_c \cos\psi_m}{c} \quad (9)$$

where $\psi_m \sim U(0, 2\pi)$.
For Rice's determined K-factor to maximize the total gain of the user channel m, equation (7) should meet the condition $\phi_n(t) = -\theta_{nm}$. For this requirement an optimal signal beam formation is realized, which in the literature is also called a coherent beam formation (Brazeetta et al., 2016; Baek et al., 2014; Chou et al., 2016).
No mechanisms were used at the measuring terminals to ensure that domestic roaming networks can measure services.
The average results of the measurements on the route under consideration are shown in the tables 1 and 2.

Table 1. Indicators for data transmission - downlink

| | | Orange | Play | Plus | T-Mobile |
|---|---|---|---|---|---|
| **Mean Data Rate- upload** | MDR [Mb/s] | 3,43 | 2,78 | 5,02 | 3,21 |
| **HTTP IP-Service Setup Time** | HIST [ms] | 1932,00 | 3428,00 | 1191,00 | 3792,00 |
| **HTTP Session Failure Ratio** | HSFR [%] | 66,31 | 71,28 | 47,28 | 61,72 |

Table 2. Indicators for data transmission - uplink

| | | Orange | Play | Plus | T-Mobile |
|---|---|---|---|---|---|
| **Mean Data Rate- upload** | MDR [Mb/s] | 0,92 | 1,18 | 1,51 | 0,9 |
| **HTTP IP-Service Setup Time** | HIST [ms] | 1741,00 | 1328,00 | 1538,00 | 2632,00 |
| **HTTP Session Failure Ratio** | HSFR [%] | 38,36 | 42,23 | 28,95 | 42,34 |

Table 3. Loss and delay rates of the packages

| | | Orange | Play | Plus | T-Mobile |
|---|---|---|---|---|---|
| **Round Trip Time** | RTT [ms] | 149,11 | 128,24 | 119,12 | 169,43 |
| **IP packet loss ratio** | IPLR [%] | 15,84 | 15,18 | 7,6 | 14,12 |
| **IP packet delay variation** | IPDV [ms] | 119,28 | 110,12 | 113,72 | 99,21 |

The studies described in Tables 1-3 give rise to the thesis that appropriate spatial planning of LTE systems allows for the resignation from dedicated development of a rail-specific system such as GSM-R. It is possible to use an open LTE system for railway purposes, both for train control and signaling but also for passenger data transmission.
The results of radio signal level tests generated from the terminals are shown in Figure 4.

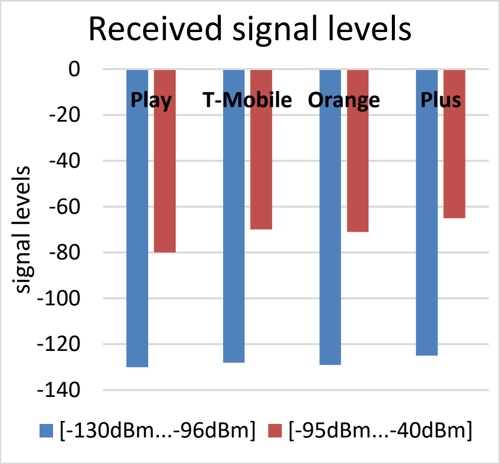



Fig. 4. Signal levels from the 4G terminals on the measurement route

On some sections of the railway line the level of signal has been decreasing, due to the fact that the communication infrastructure makes it possible to cover urban areas and roads with signal. No rolling stock was included. In the case of the propagation measurements for the LTE system in rail transport, multiway signal and vehicle interference must be included, as well as the type of material used to build the wagons. In the case of network scaling and the signal coverage of the railway lines as well, the savings are enormous (Kornaszewski et al., 2017; Chou et al., 2017). Then there is no need for dedicated communication infrastructure for the railways, because it can be replaced by an open LTE network with appropriate coding of telegrams according to PN-EN 50159:2011 standard.

## 4. Summary

On the basis of studies carried out on the constructed measuring stand (Fig.1) it can be stated that using the records of PN-EN 50159:2011 standard it is possible to create a system that is able to satisfy not only the needs of data transmission for railway traffic control devices but also passengers. The use of protection methods described in PN-EN 50159:2011 standard and the use of VPN channel additionally for the safety of VPN channel gives a guarantee of safety at the level required by standardization documents. Therefore, it seems necessary to start talks between the railway infrastructure manager and mobile operators in order to develop a network creation model based on existing operators. Creation of appropriate radio coverage of railway communication lines creates great opportunities to use systems open to railway needs, without compromising the existing transmission safety. It is necessary to remember the next stage of mobile networks development in the 5G direction. As an example of the implementation of 5G technology on railroads, we can give Nokia, which is working with German Rail (DB) on the world's first standalone 5G system for automatic train running in Hamburg as part of the highly automated DB S-Bahn project. It will be verified if the 5G technology is sufficiently sophisticated to be used as a transmission layer for the future traffic control system.

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# TICKET TARIFFS MODELLING IN URBAN AND REGIONAL PUBLIC TRANSPORT

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## *Abstract:*

*Ticket tariff is an important factor influencing the demand for public transport. Among basic problematics regarding ticket tariffs are designing new fare systems and optimization of current systems. The task of optimization is influenced by two main factors: ticket prices and the structure of the tariff. Both elements were researched in this article, based on eleven public transport organizers fare systems in Poland – metropolitan areas and cities of a different scale. The purpose of this article was to define basic tariff types used in urban and regional public transport with a presentation of their function models. Ticket tariffs split into two main groups: flat and differential. Differential group of tariffs covers: distance (usually are encountered fares based on a number of kilometres or stops travelled), quality (e.g. different fares on basic and express lines), time (minutes, hours or days of ticket validity, but also different tariff during on-peak and off-peak hours), sections (between which passenger travel on a transit route) and zones (transport network divided into areas, e.g. designated by municipalities boundaries) tariffs. The concept of this study was to transform as many tariffs as possible from tabular form to the mathematical function. Five types of functions were considered for each tariff schematic: linear, power, polynomial, logarithmic and exponential. Functions and associated with them R-squared parameters were obtained as a result of regression analysis. The paper indicates that for time, distance and flat tariffs conformity (R2) was in most cases very high and above 0,90. The results indicate that the power function best describes time tariffs. In the case of distance tariffs, different kind of functions can be used: logarithmic, power or polynomial. The proposed function form of tariffs may speed up the process of creating new fare systems or upgrading existing ones. With general knowledge about the structure of tariffs and their function forms, it would be easier to determine the price of different kinds of tickets. New fare integration solutions could be also proposed in the future by using Big Data analysis.*

***Keywords:*** *ticket tariff, fare system, fare planning, big data, public transport*

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## 1. Introduction

Modern public transport (PT in shortcut) systems are made up of five components: infrastructure, suprastructure (vehicles), ITS solutions, PT employees and organization (Chamier-Gliszczyński, 2012). Ticket tariff is an element of the organization, which can be implemented using PT employees and ITS solutions to provide service available on the infrastructure and in vehicles. It is an important criterion determining passenger demand, the others are the level of service provided by the organizer and competing transit modes (Vuchic, 2007). The level of service provided by the organizer can be assessed by checking network coverage, travel times, passenger's path choices, service frequency, etc. The level of competing services is mainly based on the accessibility of private motorization, congestion, fuel prices etc. All those criteria's specify demand elasticity on public transport services, which can be determined during the multi-criteria decision-making process (Cieśla, 2020). Those criteria can be divided into economic, environmental and social criteria (Chamier-Gliszczyński, 2017). Further on, the demand is also influenced by the maximum level of supply, which in the case of public transport can be limited by strict capacity constraints. Overcrowding effects have an impact on path choices in public transport models (Drabicki, 2017).

Among basic problematics regarding ticket tariffs are designing new fare systems and optimization of current systems. Organizers have to choose a fare system from a wide range of tariff types and adapt it to local conditions. Maximization of demand (ridership), revenue, transport performance (e.g. passenger-km), profit or social welfare are mainly chosen as the objectives of fare systems (Ling, 1998, Borndörfer, 2012). Different objectives are selected on networks covering large cities, where transport performance is more important and small communities, where social accessibility via public transport is more crucial (Danesi and Tengattini, 2020). The task of optimization is influenced by two main factors: ticket prices and the structure of the tariff. Connections between those elements were researched in this article.

The profitability of the tariffs was researched in studies held on passengers' willingness and the possibility to pay. Models have shown that passengers are most willing to pay for a journey in the cumulative pricing schematic (Otto, 2017). A robust positive relationship between workers' income and travelcard possession among low-income people was indicated. The conclusion was, that if subsidies for public transport are made because of low-income groups, the ticket pricing must be affordable for those people (Bondemark, 2020). Researches were also conducted on the topic of fare evasion by different groups of passengers. They indicated that age and gender are the main predictors of this phenomenon. Younger and male travellers have the highest likelihood to evade fares (Cools, 2018).

Problematic of ticket tariffs is inseparably connected with the unprofitability of public transport by itself, especially in systems operating in Europe. However, profitability is not the main reason for public service functioning, instead of inclusion of all social groups in society, realization of city transport policy and providing basic access to all services (work, education, culture) in the selected area. Fees from tickets are just one of the three main sources of revenues in this system, the others are subsidies or grants from city budgets and funding from the national budget or EU programs (Popović, 2018). A major influence on profitability have also ticket discounts for selected social groups, which are or not refundable by the government. Some of the transport organizers even resign from ticketing systems by the implementation of free-fare public transport, which effects depend on the quality of service, public transport usage and level of fees that existed before implementation of the system. Well identified and researched case of free-fare public transport is a city of Tallinn in Estonia (Cats, 2017).

Another major problem of ticket tariffs is the integration of different systems on a city and regional level. In most studies, it is connected with reduction of transaction costs (Takahashi, 2017), but the problem of integration is extremely challenging in fragmented public transport systems involving multiple stakeholders, such as different level of local government, transport organizers and carriers using completely different tariff systems (Iwanowicz and Szczuraszek, 2019). National legal conditions are also very limiting the possibilities for integration. New opportunities in the case of fare integration were opened by intelligent transportation systems and Big Data analysis. Systems enabled central management of income distribution to organizers and personalized fare calculation for passengers using

e.g. NFC technology (Alan and Birant, 2018). Smart cards help also to better understand demand by identifying travel patterns of individual transit riders, which enables to create large databases for service optimization (Ma, 2013). Still it must be remembered, that payment systems are just a small element of complex services provided by public transport management systems and ITS solutions generally (Karoń and Żochowska, 2015; Żochowska et al., 2018).
As it was shown above, designing ticket tariffs is a basic organizational issue of public transport. The purpose of this article is to define basic tariff types with a presentation of their function models, based on fare systems implemented in Polish public transport networks. The authors presented an original approach to the modelling of tariffs by assignment of function formulas to tariffs of a different kind. The article is divided into 6 sections. Section 2 covers a critical analysis of literaturę, regarding ticket tariff types specified all around the world; different models, which are used to determinate their form and the role of Big Data analysis. Section 3 describes the area of the research. Analysed transport organizers were listed with an indication of tariffs, which were used by them. Section 4 includes the modelling method. First, were presented methodological assumptions and then tariffs were analysed one by one. Section 5 lists the results of the study in a table presenting used tariff types with their functions and match. Finally, section 6 is devoted to the discussion of the results and conclusions.

## 2. Literature review

### 2.1. Ticket tariff types

In urban and regional public transport are used different kinds of ticket tariffs split into two main groups: flat and differential (Ling, 1998). The first is very simple because the passenger pays the same amount of money per trip, regardless of the circumstances. Among the second group, there were indicated several structures of transit fares (Grey, 1975; Nash 1982; Lovelock 1987), but all can be reduced to 5 major tariffs based on: distance (usually are encountered fares based on a number of kilometres or stops travelled), quality (e.g. different fares on basic and express lines), time (minutes, hours or days of ticket validity, but also different tariff during on-peak and off-peak hours), sections (between which passenger travel on a transit route) and zones (transport network divided into areas, e.g. designated by municipalities boundaries).
The flat tariff is presented by mentioned above authors as extremely unfair especially for passengers in greater urban areas, because both passengers travelling from one end to another of the city and the other travelling just for two stops, will pay the same amount of money. Distance tariff based on kilometres is classified as proper for intercity and regional transport (Tsai, 2008) and on the other way inconvenient in urban areas with dense stop localization. Distance tariff based on the number of travelled stops can be used in cities, but passengers must validate the ticket both while entering and exiting the vehicle, which is in turn not convenient for them. The quality tariff also disturbs passengers patience, as it must be remembered, that different services offered by the same transit organizer can cost differently. Even connections departing in the same direction on a similar route could have different prices, because one will be a basic line stopping on every stop, the other will be an express line stopping only on major interchanges. Time tariff is very popular in city and metropolitan areas, especially used for interchanging and by regular, everyday passengers of public transport. Zone tariff also uses differential ticket fees by a distance of the journey, but by assigning stops to areas (zones) and strictly depends on the localization of start and end of travel stations (origin-destination pairs) in zone system (Babel, 2003).
In-depth studies were mainly held on three types of above differential tariffs: distance, time and zone (Jørgensen and Pedersen, 2004; Otto, 2017; Yang, 2020). The major issue was, whether it is possible to achieve both a simple and efficient tariff structure. In the case of distance tariff, research has shown that dependency between fare and travel distance is less steep the higher the weight the organizer puts on profit (Jørgensen and Preston, 2007). In the case of time tariff, the one with different prices on-peak and off-peak, it is shown as a solution for overloaded transport system during peak hours. The differential tariff will influence passenger demand by reducing the number of travels during peak, in favour of off-peak hours (Marabucci, 2019). A major influence of season tickets on demand for public transport was also indicated, especially for acquiring additional everyday users (FitzRoy and Smith, 1999). In the case of zone tariff, many transport organizers use an

excessively large number of zones, which are too difficult to administrate and for passengers to navigate in. An example showed, that the ticketing system in Oslo can be simplified from 88 to only 10 zones, without any loss in functionality of the system and projected incomes (Jansson and Angell, 2012).

### 2.2. Tariff models

Selection of the optimal fare system is one of the basic issues for designing public transport system. Flat and differential tariffs were compared in case of the change of total revenue between those two general types of ticketing. The conclusion of the (Ling, 1998) research based on mathematical derivation was, that the optimal fare structure is affected by the fare elasticity of demand for short and long trips and the number of trips. (Sun and Szeto, 2019) claimed that there was no study with a comparison of more than two kinds of differentiated fare structures. Other proposed methods of assessment was a multi-criteria analysis based on the Vitas method, which results in the ranking of the zonal fare systems (Popović, 2018). Researchers mainly conduct analysis based on one prepared model of the differential tariff. Each model is constructed differently and that's the problem for comparative analysis.

The distance tariff model was presented by the relationship between demand and total costs for transport operator as a linear function influenced by the number of passengers transported and their average travel distance (Jørgensen and Preston, 2007). In the earlier study, author discussion was also conducted between transport operators emphasis on profit versus consumer surplus. The conclusion of the article was that it is not clear how travel distance influences fare, quality of transport supply and generalized travel costs, in a situation, when fare and quality are controlled variables by transport operators (Jørgensen and Pedersen, 2004).

Time fare was modelled using demand distribution between peak and off-peak hours and estimation of influence on ticket sales with different values of elasticity. Research has shown, that implementation of the tariff with more expensive tickets for peak hours and cheaper tickets for the off-peak period will increase the overall income (Marabucci, 2019). Nevertheless, there is a lack of studies taking into consideration a wide range of time tickets, on the scale of minutes, hours and days of validity. Researchers focus e.g. on single-use or season tickets separately and those offers are directed to different kinds of passengers (FitzRoy and Smith, 1999).

Model for zone tariff was first proposed using a graph-theoretical point of view on the public transportation network (Hamacher and Schöbel, 1995). Theoretical results for special networks and heuristic algorithms for the general problem were also presented (Babel, 2003). It was also indicated, that still there is a need for more sophisticated heuristics for the zone tariff problem. Zone models can vary in the way zones are designated (cut): ring structure vs. connected zones; and way the fares are calculated: counting zones, cumulative pricing and maximum pricing (Otto, 2017). The simplification of the problem was designing a zone model on rail transport networks with limited area coverage and number of stops. Optimal zone division for linear connections was also analyzed, which in the case of classification should be attributed to the sectional fare system (Yang, 2020).

The sectional fares model implies that the transit route is divided into sections. Payment is reflected in the number of sections crossed by the passenger, between boarding and alighting stops. This kind of model is adopted widely by bus companies in Hong Kong. According to the authors of the study, compared with a flat fare structure the sectional one is always better and comparing with distance-based tariff, it depends on the geometry of the network, demand distribution and maximum allowable fares (Sun and Szeto, 2019).

### 2.3. Big Data application during modelling of ticket tariffs

Access to data is a factor that can determine the position and competitive advantage of companies operating in urban and regional public transport. The concept of large, variable and diverse sets of data (Big Data) has been developed by technological solutions allowing information to be collected, then processed and finally used to construct sets of information suitable for defining the demand for service provision. In the case of public transport - in terms of designing tariff systems tailored to the specifics of a given market or optimizing existing systems (Gao et al., 2020).

Big Data in terms of application in public transport can cover many areas, including (Jabłoński, 2019): management, i.e. of substantial data sets taken, for example, from carriers' reservation systems; aggregation; cleaning, i.e. verification of large data sets; analytics understood as an analysis of large data sets; machine learning, i.e. on large data sets. In turn, the analysis of the above datasets itself may include various techniques: Data Mining; Web Mining - using internet repositories; Visualization Methods; Machine Learning; Optimization Methods and Social Network Analysis.

Digital data are being continuously collected from millions of devices. They are downloaded from the applications and analyzed to make decisions about the direction of urban transport lines (passenger route selection), frequency of trips (service provision), means of transport used, customer preferences and choices, and thus used to optimize offers, increase their efficiency, personalize them, predict user behaviour, or make real-time business decisions (Pelletier et al., 2011). Today, companies' market value is mostly based on intangible resources, including access to data, which are becoming increasingly important and start to be treated as a type of capital. Data on users and their behaviour are taken by companies, e.g. from telecoms, financial institutions involved in the ticketing process. However, they can also be generated and collected due to using products and services provided by companies providing public transport, e.g. cameras, sensors, recordings, ticket machines, applications, etc. (Gschwender, 2016).

It should be noted that very often, in this situation, we are dealing with digital data that are unstructured and cannot be stored in traditional databases. The way to use them will be using Big Data technologies to store, but above all - to process them. Therefore, data with specific parameters will be of crucial importance in supporting the definition of tariff systems. These include, among others: availability, size of data (currently calculated in terabytes or even larger units, i.e. petabytes) and the possibility to generate and process them quickly, value (separation of relevant data from those that will not be analyzed), diversity (referring to the diverse nature of both structural and non-structural data), the type and nature of data, and at the same time reliability of collected data (its veracity).

## 3. Area of analysis

For this study, 11 Polish public transport organizers have been selected and their tariffs have been listed in table 1 (Decree of Inowrocław Mayor, 2020; Decree of PKS Gdynia CEO, 2021; Gromadzki, 2011; Resolution of GZM Management Board, 2020; Resolutions of City Councils: Krakow, 2020; Lodz, 2020; Poznan, 2020; Szczecin, 2019; Torun, 2020; Warsaw, 2017 and Ząbki, 2015). In Poland, the establishment of the ticket tariff takes place mainly through resolutions of area councils or private enterprise owners. After the resolution, the tariff is implemented by the transport organizer.

In most cases, organizers use a combination of different tariff types. Most common is a combination of 2 or 3 tariffs. The basic tariff type functioning in selected organizers is based on time.

Table 1. Examples of polish urban, metropolitan or regional transport organizers tariff types

| Type of tariff \ Transport organizer | Flat | Distance (kilometres) | Distance (number of stops) | Quality | Time | Section | Zone |
|---|---|---|---|---|---|---|---|
| ZTM Warsaw | | | | | **x** | | **x** |
| ZTP Kraków | | | | | **x** | | **x** |
| UM Toruń | | | | | **x** | | **x** |
| ZTM Poznań | | | **x** | | **x** | | **x** |
| ZDIT Łódź | | | **x** | | **x** | | **x** |
| MPK Inowrocław | | | **x** | | **x** | | |
| PKS Gdynia | **x (municipality)** | **x (region)** | | | **x** | | |
| Project for LGOM (I variant) | **x (cities)** | **x (region)** | | | **x** | | |
| ZTM GZM | | **x** | | **x** | **x** | | |
| ZDiTM Szczecin | | | | **x** | **x** | | |
| UM Ząbki | **x** | | | | | | |

Passengers in that tariff have the possibility to buy short-term and long-term tickets. That fare system is used in 10 areas. In the case of large urban areas it can be combined with zoning (at least 2 zones in areas – case of Warsaw, Krakow, Torun, Poznan and Lodz), quality (e.g. more expensive tickets for airport lines – ZTM GZM situation or faster/express lines – case of ZDiTM Szczecin) or distance (based on kilometres in LGOM and ZTM GZM or number of stops travelled – cities: Poznan, Lodz and Inowroclaw) tariffs.
One private organizer – PKS Gdynia – operates on the regional area with distance fare based on kilometres, but the special feature of its tariff is a flat ticket rate inside borders of few municipalities. Also, the same fare solution is provided in the projected tariff for LGOM, but inside borders of cities (Legnica, Lubin and Głogów). The completely flat tariff was found in case of the Ząbki city, which is a small municipality inhabited by 35,000 people.

## 4. Modelling method

### 4.1. Methodological assumptions

For further modelling, all specified tariff types were subjected – flat, time, distance by a number of stops and distance by kilometres, zone and quality. The concept of this study was to transform tariffs from tabular form to the mathematical function:

$$y = f(x); \quad (1)$$

where:
y – ticket price [PLN],
x – feature of the tariff: time [h]; distance [number of stops]; distance [km]; quality or zone.

Functions were determined by using regression analysis. Five types of functions were considered for each tariff schematic:

Linear:
$$y = ax + b; \quad (2)$$
Power:
$$y = ax^b; \quad (3)$$
Logarithmic:
$$y = a \ln x + b; \quad (4)$$
Polynomial (max. of 4th degree):
$$y = a_4x^4 + a_3x^3 + a_2x^2 + a_1x + a_0; \quad (5)$$
Exponential
$$y = ae^{bx}; \quad (6)$$

where:
$a_n$, b – parameters; $n \in [0,4]$ and $n \in \mathbb{N}$.

For each tariff, the function form and coefficient of determination ($R^2$) were calculated. Functions with the highest $R^2$ were chosen as the closest possible fare model to the values presented in the tariff tables and showed on the figures with description.

### 4.2. Flat tariff

The first was modelled flat tariff of Ząbki city. In the fare, there is only one ticket type – single-trip – per 3 PLN (Resolution of Ząbki City Council, 2015). The function of this tariff is very simple: y = 3 and is not dependent on any parameter.

### 4.3. Time tariff

Time tariffs are constructed by public transport organizers in three-time intervals: minutes, hours and days. In this research four time tariffs were applied: ZTM Warsaw (Resolution of Warsaw Capital City Council, 2017), ZTP Krakow (Resolution of Krakow City Council, 2020), UM Torun (Resolution of Torun City Council, 2020) and ZDiTM Szczecin (Resolution of Szczecin City Council, 2019). It is worth noting, that those periods of ticket validity are different between the cities, some of the ticket types are used only in one of the cities: 15 minutes, 30 minutes, 45 minutes, 75 minutes, 120 minutes, 48 hours, 5 days, 10 days or 15 days valid tickets. But there are some general intervals used in every area, like tickets valid for 24 hours and 30 days. Tariffs with ticket prices were listed in table 2. For purpose of drawing a chart, validity periods have been unified to values expressed in hours.
Functions determined for the time tariffs were presented in Fig. 1.. Ticket price and time of ticket validity were shown on a logarithmic scale with a base of 2, because of multiple increments of the parameter in the case of subsequent tickets in the tariff. In all cases, time tariffs were described by power functions with the highest possible $R^2$ value. Parameter "a" of functions achieved value from interval 3,672 to 6,0512 and "b" from 0,4887 to 0,5085. Graphs of the functions marked in the diagram are very similar to each other

Table 2. Summary of ticket prices in time tariff [PLN]

| Ticket validity period | Time [h] | Ticket price [PLN] | | | |
|---|---|---|---|---|---|
| | | ZTM Warsaw | ZTP Krakow | UM Torun | ZDiTM Szczecin |
| 15 minutes | 0,25 | - | - | - | 2 |
| 20 minutes | 0,33 | 3,4 | 4 | - | - |
| 30 minutes | 0,5 | - | - | - | 3 |
| 45 minutes | 0,75 | - | - | 3,4 | - |
| 60 minutes | 1 | - | 6 | - | 4 |
| 75 minutes | 1,25 | 4,4 | - | - | - |
| 90 minutes | 1,5 | 7 | 8 | 6 | - |
| 120 minutes | 2 | - | - | - | 5 |
| 24 hours | 24 | 15 | 17 | 12 | 12 |
| 48 hours | 48 | - | 35 | - | - |
| 72 hours | 72 | 36 | 50 | - | - |
| 5 days | 120 | - | - | - | 35 |
| 7 days | 168 | - | 56 | 43 | - |
| 10 days | 240 | - | - | - | 60 |
| 15 days | 360 | - | - | 53 | - |
| 30 days | 720 | 110 | 148 | 88 | 100 |
| 90 days | 2160 | 280 | - | 240 | 260 |

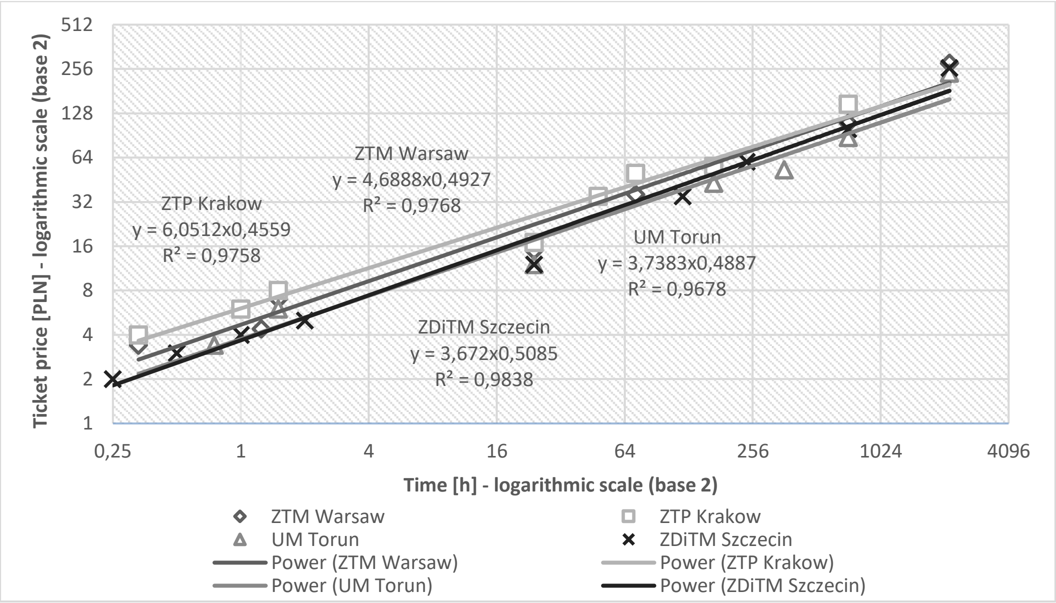


Fig. 1. Regression analysis of tariffs based on time

### 4.4. Distance (number of stops) tariff

Distance tariff with counting number of stops are constructed by public transport organizers in two different ways: by adding a fee to every additional travelled stop or by setting a price for several stops travelled in ranges. In the analysis, the first option is used by ZDiT Lodz [34] and ZTM Poznan [35], the second – by MPK Inowroclaw [29]. Inowroclaw tariff is almost flat – there are only 3 price levels, which does not differ much. It is connected with a small size of the city (72,000 inhabitants) and rather short routes of the bus lines. In all cases, the fare system limits a maximum of 30 possible stops on the route. Complete distance tariffs with ticket prices were listed in table 3. The further the passenger trip is heading, the less the ticket price is incremented. In each case, tariffs were described by other types of function. ZTM Poznan fare system was regressed into a logarithmic function, MPK Inowroclaw to a polynomial of 4th degree and ZDiT Lodz to a power function. In each situation, the $R^2$ parameter was above 0,93 and very close to 1 in the case of logarithmic and power regression (respectively 0,9932 and 0,996). Functions were presented in Fig. 2.

### 4.5. Distance (kilometres) tariff

Distance tariffs with the counting of kilometres travelled are mainly constructed based on distance ranges in which passengers pay the same fare for a selected number of kilometres. The analysis covered two examples of transport organizers with this kind of fare system: PKS Gdynia (Decree of PKS Gdynia CEO, 2021) and ZTM GZM (Resolution of GZM Management Board, 2020); and also one based on project proposition for the LGOM area (Gromadzki, 2011). In urban areas, this type of tariff is flatter, than in the case of regional transport, where the increment of fare is steeper.

Table 3. Summary of ticket prices in distance (number of stops) tariff [PLN]

| **Number of stops** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|---|
| ZTM Poznan | 0,72 | 1,32 | 1,92 | 2,32 | 2,72 | 2,90 | 3,08 | 3,16 | 3,24 | 3,32 |
| MPK Inowroclaw | 2,30 | 2,30 | 2,50 | 2,50 | 2,50 | 2,70 | 2,70 | 2,70 | 2,70 | 2,70 |
| ZDiT Lodz | 1,00 | 1,20 | 1,40 | 1,60 | 1,80 | 2,00 | 2,20 | 2,30 | 2,40 | 2,50 |
| **Number of stops** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** |
| ZTM Poznan | 3,40 | 3,48 | 3,56 | 3,64 | 3,72 | 3,80 | 3,88 | 3,96 | 4,04 | 4,12 |
| MPK Inowroclaw | 2,70 | 2,70 | 2,70 | 2,70 | 2,70 | 2,70 | 2,70 | 2,70 | 2,70 | 2,70 |
| ZDiT Lodz | 2,60 | 2,70 | 2,80 | 2,88 | 2,96 | 3,04 | 3,12 | 3,20 | 3,28 | 3,36 |
| **Number of stops** | **21** | **22** | **23** | **24** | **25** | **26** | **27** | **28** | **29** | **30** |
| ZTM Poznan | 4,18 | 4,24 | 4,30 | 4,36 | 4,42 | 4,48 | 4,54 | 4,60 | 4,66 | 4,72 |
| MPK Inowroclaw | 2,70 | 2,70 | 2,70 | 2,70 | 2,70 | 2,70 | 2,70 | 2,70 | 2,70 | 2,70 |
| ZDiT Lodz | 3,42 | 3,48 | 3,54 | 3,60 | 3,66 | 3,72 | 3,78 | 3,84 | 3,90 | 3,96 |

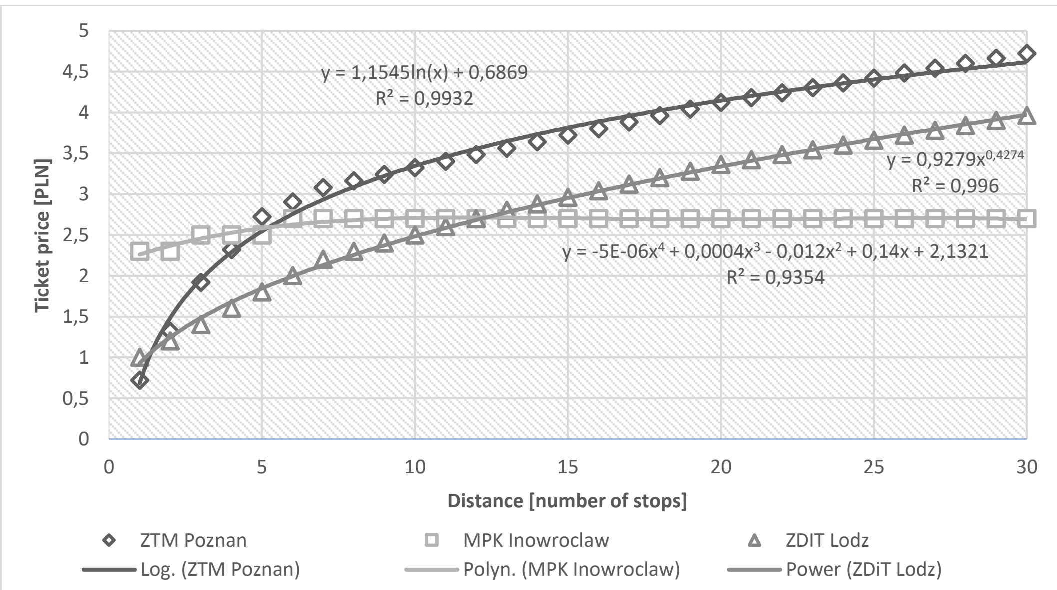


Fig. 2. Regression analysis of tariffs based on distance (number of stops)

The maximum travel distance in this tariff depends on the size and organization of the transport network.In the ZTM GZM network, the longest possible route is 50-kilometres long, in LGOM 80 kilometres and in PKS Gdynia it is limited to 140 kilometres. Only single-trip tickets were analyzed in this kind of tariff, but in the offer of some of the transport organizers, there are also season tickets connected with a distance range of trips. Complete distance tariffs with ticket prices were listed in Table 4.
Two tariffs were described by polynomial functions of 2nd (LGOM) and 4th degree (PKS Gdynia) and one by logarithmic function (ZTM GZM). This happened due to fare construction – rather systematic increase of ticket price with the length of the journey or large discount for short journeys and a rather flat rate for longer ones. In each situation, the $R^2$ parameter was above 0,9 and very close to 1 in the case of polynomial regressions (values of 0,9915 and 0,9885). Functions were presented in Fig.3.

### 4.6. Zone tariff

Zone tariff is often combined by Polish public transport organizers with time tariff. The second characteristic element of zoning in Poland is also division on a low number of zones: 2 or 3. Generally, they are cut on the area of city and suburban municipalities. In the case of Krakow, the third zone is designated on further metropolitan municipalities areas. Availability of different kind of time tickets in selected zones of the organizer is very low – tickets are mainly available only in the I zone (area of the main city) or in all zones. Best availability is represented by 30 days tickets. Zone tariffs with ticket prices were listed in Table 5.

Table 4. Summary of ticket prices in distance (kilometres) tariff [PLN]

| Distance [km] | 1 | 2 | 3 | 4-5 | 6-8 | 9 | 10 | 11-13 | 14 | 15 | 16-20 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| PKS Gdynia | 5,0 | 5,0 | 5,0 | 6,0 | 6,5 | 7,0 | 7,0 | 7,5 | 8,0 | 8,0 | 9,0 |
| LGOM | 3,0 | 3,0 | 3,0 | 3,0 | 4,0 | 4,0 | 4,0 | 4,5 | 4,5 | 4,5 | 5,0 |
| ZTM GZM | 1,6 | 2,2 | 2,8 | 2,8 | 3,4 | 3,4 | 3,9 | 3,9 | 3,9 | 4,2 | 4,2 |
| **Distance [km]** | **21-25** | **26-30** | **31-35** | **36-40** | **41-45** | **46-50** | **51-55** | **56-60** | **61-70** | **71-80** | **>80** |
| PKS Gdynia | 9,5 | 10,0 | 11,0 | 12,0 | 13,0 | 15,0 | 16,0 | 17,0 | 18,0 | 20,0 | 20,0 |
| LGOM | 5,5 | 6,0 | 7,0 | 7,0 | 8,0 | 8,0 | 9,0 | 9,0 | 10,0 | 11,0 | - |
| ZTM GZM | 4,4 | 4,4 | 4,4 | 4,4 | 4,4 | 4,4 | - | - | - | - | - |

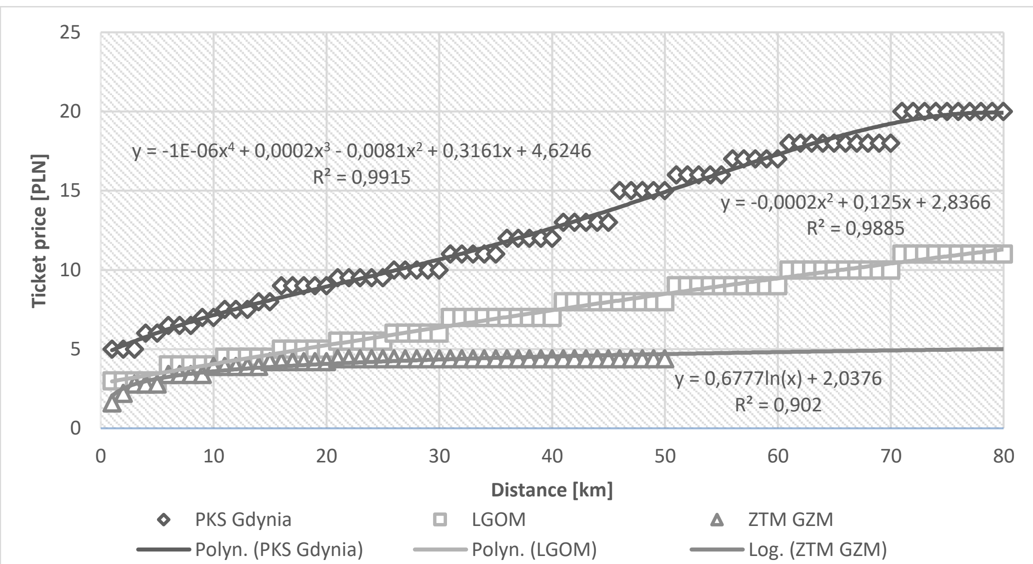


Fig. 3. Regression analysis of tariffs based on distance (kilometres)

Table 5. Summary of ticket prices in zone tariff [PLN]

| Ticket validity period | ZTM Warsaw | | | ZTP Krakow | | | | | | UM Torun | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Zone I | Zone II | Zone I+II | Zone I | Zone II | Zone III | Zone I+II | Zone II+III | Zone I+II+III | Zone I | Zone I+II |
| 20 minutes | - | - | 3,4 | - | - | - | - | - | 4 | - | - |
| 45 minutes | - | - | - | - | - | - | - | - | - | - | 3,4 |
| 60 minutes | - | - | - | - | - | - | - | - | 6 | - | - |
| 75 minutes | 4,4 | - | - | - | - | - | - | - | - | - | - |
| 90 minutes | - | - | 7 | - | - | - | - | - | 8 | - | 6 |
| 24 hours | 15 | - | 26 | 17 | - | - | - | - | 22 | - | 12 |
| 48 hours | - | - | - | - | - | - | - | - | 35 | - | - |
| 72 hours | 36 | - | 57 | - | - | - | - | - | 50 | - | - |
| 7 days | - | - | - | 56 | - | - | - | - | 68 | - | 43 |
| 15 days | - | - | - | - | - | - | - | - | - | 53 | - |
| 30 days | 110 | 112 | 180 | 148 | 79 | 37 | 158 | 96 | 179 | 88 | 126 |
| 90 days | 280 | 282 | 460 | - | - | - | - | - | - | 240 | - |

Selective nature of zone tariff unable to perform modelling of a coherent function forms for this kind of fare system.

### 4.7. Quality tariff

The quality tariff is rare in urban public transport, but in an analyzed set of organizers, there are two specific situations, in which organizations use them. ZTM GZM for three ticket types has extended tariff including whole public transport network with special express lines going to the Katowice Airport. The tariff is available only with 24 hours, 30 and 90 days network tickets. Basic ticket prices are multiplied by 1,16 or 1,40 to achieve an extended tariff (Resolution of GZM Management Board, 2020). Differ in the quality tariff of the organizer is presented in table 6.

Table 6. Summary of ticket prices in quality ZTM GZM tariff [PLN]

| Ticket validity | 24 hours | 30 days | 90 days |
|---|---|---|---|
| Network without airport line | 10 | 134 | 344 |
| Network with airport express lines | 14 | 160 | 400 |
| Conversion factor | 1,40 | 1,16 | 1,16 |

ZDiTM Szczecin network is divided into normal and express lines. The tariff is available only in case of minute and monthly tickets, but without a 120 minutes ticket, because there is no express line with such a long travel time of a single journey. Express lines tariff is achieved by multiplying the basic price by 1,62 (monthly tickets) or 2,00 (single tickets). Differ in the quality tariff of the organizer is presented in table 7.

The above-mentioned tariffs are very specific and it was not possible to designate a coherent function form of them.

## 5. Statement of results

Functions and R-squared obtained as a result of regression for different ticket fares were listed in table 8. The simplest function was obtained in the case of the flat tariff. Power functions determined mainly time fare systems, but with a very high $R^2$ parameter (above 0,96). Polynomial functions were best assimilated to the distance fares – both connected with counting stops or kilometres. In some situations, distance tariffs were also represented by logarithmic and power functions. The lowest obtained $R^2$ value was 0,9020 (distance tariff of ZTM GZM) and the biggest one 0,9960 (distance tariff of ZDIT Lodz), which is extremely close to the actual tariff form.

Table 7. Summary of ticket prices in quality ZDiTM Szczecin tariff [PLN]

| Ticket validity | 15 minutes | 30 minutes | 60 minutes | 120 minutes | 30 days | 90 days |
|---|---|---|---|---|---|---|
| Normal lines | 2 | 3 | 4 | 5 | 100 | 260 |
| Express lines | 4 | 6 | 8 | - | 162 | 422 |
| Conversion factor | 2,00 | 2,00 | 2,00 | - | 1,62 | 1,62 |

Table 8. Summary of regression functions and r-squares for different ticket fares

| Transport organizer | Analyzed type of tariff (x) | The function of ticket price [PLN] | Type of regression | **Match $R^2$** |
|---|---|---|---|---|
| UM Ząbki | **Flat** | **y = 3** | **-** | **-** |
| ZTM Warsaw | **Time** | $y = 4,6888x^{0,4927}$ | **power** | 0,9768 |
| ZTP Krakow | **Time** | $y = 6,0512x^{0,4559}$ | **power** | 0,9758 |
| UM Torun | **Time** | $y = 3,7383x^{0,4887}$ | **power** | 0,9678 |
| ZDiTM Szczecin | **Time** | $y = 3,672x^{0,5085}$ | **power** | 0,9838 |
| ZTM Poznan | **Distance (number of stops)** | y = 1,1545ln(x) + 0,6869 | **logarithmic** | 0,9932 |
| ZDIT Lodz | **Distance (number of stops)** | $y = 0,9279x^{0,4274}$ | **power** | 0,9960 |
| MPK Inowroclaw | **Distance (number of stops)** | $y = -5E-06x^4 + 0,0004x^3 - 0,012x^2 + 0,14x + 2,1321$ | **polynomial** | 0,9354 |
| PKS Gdynia | **Distance (kilometers)** | $y = -1E-06x^4 + 0,0002x^3 - 0,0081x^2 + 0,3161x + 4,6246$ | **polynomial** | 0,9915 |
| Project for LGOM | **Distance (kilometers)** | $y = -0,0002x^2 + 0,125x + 2,8366$ | **polynomial** | 0,9885 |
| ZTM GZM | **Distance (kilometers)** | y = 0,6777ln(x) + 2,0376 | **logarithmic** | **0,9020** |

## 6. Conclusions

Problematic of ticket tariffs are complex and have many areas to be researched. The basic research issue is that public transport organizers use different kinds of ticket tariffs. As it was shown in this paper, in most cases, there is no one tariff implemented in the transport system, but a combination of different models on a single area. The most common is a combination of 2 or 3 tariffs. Only 1 on 11 selected organizers from Poland used just one tariff and it was a flat one. That kind of tariff is rather used in small cities and the whole set of other types of tariffs in larger areas. The group of differential tariffs was specified in the research and it included time, distance (kilometres or number of stops), section, zone and quality fare systems. In the case of demand analysis, which could be the continuation of this research, the situation of coexisting multiple ticket tariffs should be taken into consideration.

As it was shown in this research, flat, time or distance tariffs can be approximated from tabular to function form after making the regression. Their match is in most cases very high and above 0,90. The power function is best for describing time tariffs. In the case of distance tariffs, different kinds of functions can be used: logarithmic, power or polynomial. Function form of tariffs may speed up the process of creating the new fare system. With general knowledge about the structure of tariffs and their function forms, it would be easier to determine the price of different kinds of tickets, which would be based on the experience of existing systems. So the results of this study can be used in designing the process of new tariff systems. This problem can be also researched further to find typical models describing each tariff and some basic, repeatable parameters.

The type of function achieved in regression of tariffs can be connected with its features, which are benefitting longer journeys with less addition to the travel cost (degressive tariff). Such an approach to fare policy is specific for urban and regional public transport. Deeper studies can be conducted on comparison of different tariff types used in one area – for example, time and distance tariffs in Poznan and Lodz. The literature review showed that researches are mainly conducted on one ticket tariff system, while the biggest problem is the interference of those solutions. The influence of both fare systems should be assessed as well as, which tariff is more attractive to passengers or more profitable for transport organizer.

Functions describing tariffs can be also used to create more types of tickets within existing tariffs, for the reason of creating a more user-friendly system. By using ITS solutions organizers can implement electronic pay as you go systems with a wide range of tickets, regardless of the offer which was created for paper tickets. The advantage of such a system would be better matching to passenger's needs, for example by creating an offer for any multiple number of days travelled. As it was indicated in the research, nowadays there are some specific periods of

ticket validity, limited by the possibility of performing operations with paper tickets.
The problem of tariff diversity is very complex, especially in the situation of few transport organizers functioning in the area, e.g. urban transport, railway and regional bus transport, and integration of them into one coherent system. This issue can be researched further using Big Data analysis for finding the solution for the integration problem, that will connect or create new tariffs. Models for integration should take into consideration existing law, the structure of incomes, areas of communes, demand for transport etc.
Data processing techniques could be applied, so the transport companies will build competitive advantage strategies and thus improve their business models to increase their operations' efficiency, including the improvement of their operational performance. Big Data, therefore, would help to gain a deeper understanding of the micro and macro environment of modern public transport, including its users, in order to be able to design a better fare system.

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# ANALYSIS OF THE CONDITIONS FOR THE EXHAUSTION OF THE STABILITY MARGIN IN THE RAIL TRACK OF FREIGHT CARS WITH THREE-PIECE BOGIES

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## *Abstract:*

*The research on improvement of methodical approaches to definition of the probable reasons of infringement of conditions of stability of freight cars from derailment is carried out. Using a basic computer model of the dynamics of a freight car, the influence of the characteristics of the technical condition of their running gear and track on the indicators of empty cars stability from derailment was studied through the computational experiment.*
*The article presents the main statements of the research methodology, which provides the analysis of probable causes of derailment of freight cars by conducting a series of numerical experiments with logging the progress of calculations and saving the results. Factor analysis was used to interpret the calculated data with an assessment of each of the factors influence or their combination on the probability of derailment.*
*The developed procedure of the simulation experiment provides a step-by-step study of the freight cars derailment conditions, including factors structuring and ranking, development of experimental plan, calculating coefficients of wheel pairs resistance to derailment from rails, provided that the wheel flange rolls onto the rail head, and determining the degree of influence of relevant factors on the dynamic stability of cars from derailment. A comparative analysis of the stability of cars in rail tracks was performed using the introduced concept of the combined coefficient of stability of wheel pairs against derailment.*
*Determining the probable causes of car derailment is based on scanning the parameter field. The results of the parametric study revealed the degree of influence on the freight cars stability of running gear technical condition characteristics. In particular, it is determined that the most dangerous in terms of stability loss of empty cars in the track is the exceeding of the wedges of the vibration dampers.*

**Keywords:** *freight cars, derailment, computer simulation, traffic safety, dynamic performance*

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## 1. Introduction

Railway accidents involving the derailment of rolling stock depend on many factors, both objective and subjective. Due to the combined action of many factors, some of which are not recorded by objective means of control during the movement of the train, the analysis of emergency situations is not always possible to identify and explain the cause of the derailment. At the same time, the assessment of traffic safety indicators according to existing methods does not reflect the actual conditions that increase the risks of derailment.

Railway safety as a key issue includes a wide range of components, among which a leading place belongs to the dynamics of vehicle motion (Ashtiani, I., et al., 2017; Burdzik, R., et al., 2017; Dusza, M., 2014; Garg, V.K., Dukkipati, R.V., 1984; Kardas-Cinal, E., 2013; Wickens, A.H., 2003). In the mechanical sense, the level of operational safety of railway vehicles is mainly determined by the margin of stability in the track (Domin, R., et al., 2017; Fan, Y-T., et al., 2006; Molatefi, H., 2016; Opala, M., 2016). Therefore, in the field of mechanics of rolling stock, the role of research work to study the course of dynamic processes that affect the emergencies occurrence conditions associated with rolling stock derailment, remains acute at all stages of railway transport development (Domin, R., et al., 2019; Iwnicki, S., et al., 2015; Malcolm, C., 2016; Saviz, M.R., 2015; Wilson, N., et al., 2011).

A characteristic feature of the spatial oscillations of vehicles, the movement of which is directed by the rail track, is the tendency under certain conditions to self-excitation of auto-oscillations (Mazilu, T., 2009). The lowest value of the speed at which unquenchable lateral oscillations of a railway vehicle occur, is called the critical speed of hunting $V_{cr}$. Transverse hunting oscillations of bogies when moving at speeds exceeding the critical, cause excessive lateral forces of the wheels on the track, increase the damage of freights sensitive to dynamic loads, and lead to additional damage to rolling stock and railway infrastructure. In addition, the extra energy of the locomotive is spent on maintaining a constant speed of the train composed of cars, the movement of which is complemented with self-oscillations. Thus, the critical hunting velocities determine the limits of threshold changes in the dynamic properties of railway vehicles.

Self-excitation of lateral oscillations of railway vehicles is caused by their loss of stability of undisturbed motion. Effective use of methods of mechanical stability theory in relation to studies of the dynamics of the movement of railway vehicles, in particular the first approximation of A.M. Lyapunov (Lyapunov, A.M., 1956), first carried out by academician V.A. Lazaryan (Lazaryan, V.A., 1964).

## 2. Dynamic phenomena contributing to emergencies related to rolling stock derailment occurrence

Obviously, each transport event is associated with a coincidence of a number of adverse circumstances, among which, however, there is always a leading cause. The low freight cars stability margin from derailment is most often caused by their unsatisfactory dynamic properties which are mainly explained by design features and a technical condition of running gear (Galiev, I.I., et al., 2011).

According to the results of numerous studies and investigations of transport accidents, it turns out that the objects of emergency situations are increasingly freight cars in an empty state (Ge, X., et al., 2018; Ermakov, V.M., Pevzner, V.O., 2002). Empty cars with a high center of mass (bunker cars, tank cars, etc.) are most prone to loss of stability in the rail track.

### 2.1. Resonant movement modes of freight car in empty state

It is known that the spring suspension of freight cars of 1520 mm gauge in the empty state can partially or completely lose its damping properties due to the weakening or complete exclusion from the operation of wedge vibration dampers caused by the so-called exceeding of the wedges. At the same time rigidity of a spring suspension bracket of the bogie can decrease in 1.4 times. This situation leads to a decrease in the natural frequencies of the car, and hence a decrease in the speed at which the resonant mode occurs.

Periodic perturbations that cause resonant modes of rolling stock are associated with both periodic irregularities of the track and the existing defects on the rolling surfaces of car wheels. Therefore, in the spectrum of perturbations acting on a moving car, there are always components with the frequency of rotation of the wheel pairs. These components, even with the permissible defects of the wheels, are sufficient for the development of resonant phenomena, when the speed of the car reaches a critical value when the wheel pair rotation speed $f_w$ with one of the natural frequencies $f_i$ . These velocities are called resonant. So the resonant speed $V_r$ is calculated by expression $V_r = L_w \cdot f_i$ , where $L_w$ – is the length of the wheel rolling circle.

Fig. 1 shows a diagram for determining the resonant velocities. Here, rays I and II show the dependences of the speed of wheel pairs with the full (I) and limiting (II) thickness of the wheel rims. Resonant velocities $V_r^{(i)}$ ($i$ = 1…4) are at the points of intersection of lines I and II with the horizontal natural frequencies of vertical oscillations $f_v$ and $f_v^*$ respectively at nominal and reduced (due to the exclusion of underwedge springs) stiffness of the suspension. Thus, under operating conditions, the resonant velocities can take values in the range from $V_r^{(1)}$ to $V_r^{(4)}$.

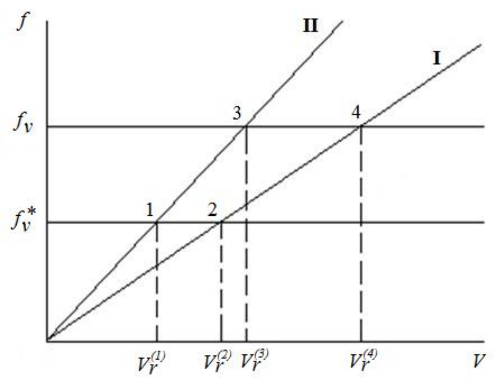

Fig. 1. Scheme for determining resonant velocities

The most dangerous for empty cars is the $V_r^{(1)}$ - $V_r^{(2)}$ speed range, which corresponds to cases of insufficient or absent damping of oscillations (Fig. 1). In the resonant modes of oscillations of bouncing and pitching at the moments of full unloading of wheels in case of horizontal forces cross there is a real threat of derailment.

The natural frequencies of oscillations of the freight car bodies of some types in the empty state are shown in Table 1. Oscillation frequencies of bouncing $f_b$ and $f_b^*$, pitching $f_p$ and $f_p^*$ and rolling $f_r$ and $f_r^*$ calculated according to two values of the stiffness of the spring suspension, corresponding to the nominal stiffness of the spring sets (numerator) and reduced due to the exclusion from the normal operating state of the wedge vibration dampers (denominator).

Table 1. Natural frequencies of freight car bodies oscillations in Hz at the nominal and reduced spring suspension stiffness

| Oscillation type | Car types | | | |
|---|---|---|---|---|
| | gondola car | covered car | hopper car | tank car |
| Jumping | 5,61/4,74 | 5,22/4,41 | 5,50/4,60 | 5,16/4,36 |
| Galloping | 6,61/5,59 | 6,42/5,43 | 7,60/6,46 | 5,80/4,90 |
| Lateral oscillation | 5,02/4,24 | 4,00/3,38 | 4,14/3,50 | 3,99/3,36 |

According to the calculated frequencies, the resonant speeds of the considered types of cars with new and worn wheels are determined. For example, Fig. 2 shows the range of resonant velocities of the empty gondola car at full and maximum thickness of the wheel rim, respectively, at nominal and reduced stiffness of the suspension, taking into account the calculated frequencies (Table 1). Lines 1, 2, 3 correspond to frequencies $f_b$, $f_p$ and $f_r$ and lines 4, 5, 6 – to frequencies $f_b^*$, $f_p^*$ and $f_r^*$. Dependences of frequencies of rotations of wheelsets on full $f_f(v)$ and limit $f_{ut}(v)$ the wheel rims thicknesses that corresponding to the wheel radii of 0.475 and 0.425 m are represented by graphs 7 and 8.

As can be seen from the graphical data, the values of resonant velocities for the gondola car are in the range of 41 – 71 km/h. According to similar calculations, the values of resonant velocities for other types of cars were obtained. Depending on the models of freight cars, the condition of the wedge dampers and the thickness of the rims of their wheels, the resonant speeds can vary in wide ranges: 32 – 69 km/h for a covered car; 33 – 82 km/h for a hopper car; 32 – 62 km/h for a tank car. Thus, it can be stated that these values of resonant speeds are covered by the operating speeds of freight trains on the railways of 1520 mm. From the point of view of traffic safety, this fact requires increasing the requirements for monitoring the technical condition of the spring suspension and wheelsets.

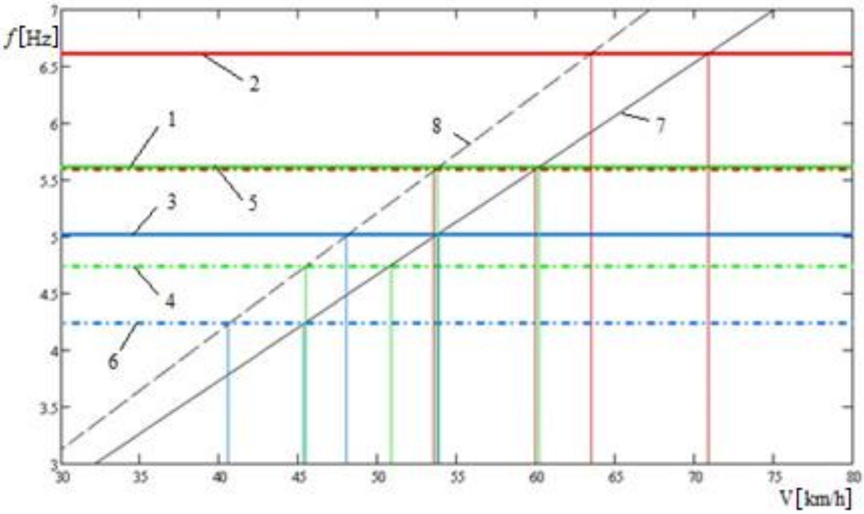


Fig. 2. Resonant velocities of the gondola car

### 2.2. Stability of rolling stock in rail track

Freight cars of 1520 mm track are equipped exclusively with three-element bogies, the characteristic feature of which, from the point of view of mechanics, is the saturation of units with open pairs of dry friction. This circumstance significantly complicates the analysis of stability conditions in the rail track of cars as essentially nonlinear systems.

Due to the presence of open pairs of dry friction in the combinations of bearing elements of the running gear between themselves and the body, it is possible to stop in the relative movements of individual bodies of the system, which includes the model of the freight car. Thus, the system may lose degrees of freedom and move from one structural state to another. Therefore, the original design system of the car can be considered as a system with a variable structure. The number of possible structural states of such system is equal to $2^i$ ($i$ – number of friction nodes).

Based on the concept of fundamental variability of the output system, which simulates the dynamic behavior of a freight car, a method for determining critical velocities using linearization of discrete systems with dry friction units was proposed (Diomin, Yu.V., et al., 1994). The essence of this method is to replace the original nonlinear system with $l$ linear subsystems ($l = 2^i$). Each of $l$ subsystems corresponds to one of the possible states of the original nonlinear system. Such subsystems are built in accordance with the structural changes of the original system due to the alternate closure of connections with dry friction.

When constructing linear subsystems, the main thing is to determine the parameters of viscous friction, which replaces dry friction in open joints. According to the developed method of formation of linear subsystems for determining the coefficient of equivalent viscous resistance $\beta^l_{i-j}$ in $i-j$ connection of a multi-mass self-oscillating system is carried out according to a formula similar to that used by S.P. Tymoshenko in the study of forced oscillations of the oscillator with dry friction (Weaver, W. Jr., et al., 1990). Regarding the model of operation of the body support devices on the bogies during their mutual turns, the mentioned formula has the form

$$\beta^l_{1-i} = 4W / \pi \cdot \Delta\psi_{1-j} \cdot \omega, \qquad (1)$$

where: $\Delta\psi_{1-j}$ – amplitude values of angles of mutual turns of a body and bogies; ω – frequency of self-oscillations.

Values of $\Delta\psi_{1-j}$ and ω are determined by an iterative method based on the step-by-step solution and analysis of the complete problem of eigenvalues of matrices of coefficients of equations of motion of subsystems of type $\dot{x} = A^{(l)} \cdot x$ . The stability of possible states of the system (subsystems) is estimated. The value is taken as an indicator of stability is $h_{\max}^{(l)} = \max(\mathrm{Re}\,\lambda_i^{(l)})$ , where $\lambda_i^{(l)}$ - eigenvalues of matrices $A^{(l)}$ . A critical speed is determined for each system $V_{cr}^{(lm)}$ as the value of speed $V$ at $h_{\max}^{(l)} = 0$ , or $h_{\max}^{(l)}(V_{cr}^{(l)}) = 0$ . The smallest of the critical velocities of the obtained range is the speed of movement $V_{so}$, in which there are self-oscillations in the studied system with dry friction, thus

$$V_{so} = \min\left|V_{cr}^{(1)}, V_{cr}^{(2)}, \ldots, V_{cr}^{(l)}\right| . \quad (2)$$

The indicators of stability of the least stable of a number of subsystems, which approximated the original system, determine the conditions of self-oscillations of the studied railway vehicle. Thus, the method of structural linearization allows to extend powerful methods of linear algebra to a class of systems that are not fundamentally linearizable.

## 3. Study of influence on stability of cars from derailment of running gears elements technical condition characteristics

A basic computer model of the dynamics of a four-axle car with three-element bogies, developed with the help of a software package UM (Cherniak, A., 2013; Pogorelov, D.Yu., 2005) was used to study and identify the probable reasons for the derailment of freight cars. This model allows to obtain modifications of dynamic models of freight cars of the main types (gondola cars, covered cars, hopper cars, tank cars), which differ in the design of bodies, but have typical running gears (Domin, R., et al., 2016). The computer model of the dynamics of a freight car provides a detailed description of the technical condition of the running gears of freight cars that have derailed. This makes it possible to adjust the specialized parameters of the model, in particular those that characterize the technical condition of the running gears of the derailed car, and the characteristics of the derailment track section.

### 3.1. Estimation of stability margin of wheel sets from derailment

A necessary step in determining the prerequisites for derailment is to study the influence of certain factors on the characteristics of the dynamic processes that accompany the movement of the car. The assessment of dynamic characteristics should be the selected indicators of the margin of stability of wheel sets from derailment under the condition of rolling the wheel flange on the rail head, which comprehensively characterize the combination of both horizontal and vertical forces acting simultaneously on the wheel of each wheel set. On 1520 mm gauge railways, the main indicator of rolling stock safety is the so-called coefficient of stability of wheel set from derailment, provided that the wheel flange rolls onto the rail head. (Standards, 1996). Coefficient of stability of wheel against derailment $k_{dr}$ when moving the car with the maximum speed on the straight track of good condition with combinations of deviations in the plan, skews and sags allowed, is calculated by the formula:

$$k_{dr} = \frac{tg\beta - \mu}{1 + \mu \cdot tg\beta} \cdot \frac{P_v}{P_h} \geq (k_{dr})_{\lim} , \quad (3)$$

where: $\beta$ – the angle of inclination to the horizon of the generating conical surface of the wheel crest, for the wheels 1520 mm gauge cars $\beta = 60^{\circ}$; $\mu$ – coefficient of sliding friction of interacting surfaces of wheels and rails (in calculations it is considered $\mu$ = 0,25); $P_v$ – vertical component of the forces impacting from the wheels on the rails; $P_h$ – the horizontal component of the forces of interaction of the wheel with the rail, which impacts simultaneously with the force $P_v$. For freight cars of 1520 mm gauge the maximum allowable value is $(k_{dr})_{\lim} = 1.3$.

Execution of the analysis of probable reasons of derailment of freight cars requires carrying out of a series of numerical experiments, according to the plan made in advance, with course of calculations logging and preservation of results. The general procedure of the simulation experiment to study the of freight cars derailment conditions is reduced to the following stages:

- structuring and ranking of factors influencing the stability of cars in the track;
- conducting an experimental plan;
- calculation of stability coefficients of from derailment of wheelsets on condition of wheel flange rolling on a rail head;

– determining the degree of relevant factors influence on the dynamic stability of cars from derailment.

The probable causes of car derailing are determined on the basis of computer simulations based on a scan of the parameters field. This method provides complete information about the objective function within the defined parameter sets. The number of computer experiments when scanning is calculated as $N = m^k$, where $k$ is number of varying factors, $m$ is the number of levels at which each factor varies. Depending on the number of factors and the levels of each of them selected for the scan, the number of options is growing rapidly. Thus, the time of scanning and computational costs, increases significantly.

In the task for scanning, in addition to the speed $V$, as study factors the following characteristics of the undercarriage were selected: *fp* – friction coefficients in center bearing nodes; *wp* – dislocation of center bearing nodes in the longitudinal direction; *fs* – friction coefficients in the side slides; *kl* – exceeding of wedges of bogies; *wb*1 and *wb*2 – clearances in the longitudinal direction between the axle boxes and side frames, respectively, for the first and the second bogies. For each of the selected factors, the determined levels are shown in Table 2.

Table 2. Factors levels

| Levels | *fp* | *wp* [m] | *fs* | *kl* [m] | *wb*1[m] | *wb*2[m] |
|---|---|---|---|---|---|---|
| 1 | 0,1 | 0 | 0,1 | 0 | 0 | 0 |
| 2 | 0,4 | 0,005 | 0,4 | 0,015 | 0,004 | 0,004 |
| 3 | | | | | 0,008 | 0,008 |

The full-factorial plan of the experiment as a plan of the conducted experiments takes into accounts all possible combinations of levels of each factor. According to the identified factors, a full-factorial plan of the experiment with the total number of variants 144 was formed (Table 3). An experiment with such a plan allows us to quantify the effects of both individual factors and the interaction of factors (Adler, Yu., et al, 1971).

Table 3. Estimated variants for the running gears technical condition

| Variants numbers | *fp* | *wp* [m] | *fs* | *kl* [m] | *wb*1[m] | *wb*2[m] |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 1/2/3 | 0,1 | 0 | 0,1 | 0 | 0 | 0/0,004/0,008 |
| 4/5/6 | 0,1 | 0 | 0,1 | 0 | 0,004 | 0/0,004/0,008 |
| 7/8/9 | 0,1 | 0 | 0,1 | 0 | 0,008 | 0/0,004/0,008 |
| 10/11/12 | 0,1 | 0 | 0,1 | 0,015 | 0 | 0/0,004/0,008 |
| 13/14/15 | 0,1 | 0 | 0,1 | 0,015 | 0,004 | 0/0,004/0,008 |
| 16/17/18 | 0,1 | 0 | 0,1 | 0,015 | 0,008 | 0/0,004/0,008 |
| 19/20/21 | 0,1 | 0 | 0,4 | 0 | 0 | 0/0,004/0,008 |
| 22/23/24 | 0,1 | 0 | 0,4 | 0 | 0,004 | 0/0,004/0,008 |
| 25/26/27 | 0,1 | 0 | 0,4 | 0 | 0,008 | 0/0,004/0,008 |
| 28/29/30 | 0,1 | 0 | 0,4 | 0,015 | 0 | 0/0,004/0,008 |
| 31/32/33 | 0,1 | 0 | 0,4 | 0,015 | 0,004 | 0/0,004/0,008 |
| 34/35/36 | 0,1 | 0 | 0,4 | 0,015 | 0,008 | 0/0,004/0,008 |
| 37/38/39 | 0,1 | 0,005 | 0,1 | 0 | 0 | 0/0,004/0,008 |
| 40/41/42 | 0,1 | 0,005 | 0,1 | 0 | 0,004 | 0/0,004/0,008 |
| 43/44/45 | 0,1 | 0,005 | 0,1 | 0 | 0,008 | 0/0,004/0,008 |
| 46/47/48 | 0,1 | 0,005 | 0,1 | 0,015 | 0 | 0/0,004/0,008 |
| 49/50/51 | 0,1 | 0,005 | 0,1 | 0,015 | 0,004 | 0/0,004/0,008 |
| 52/53/54 | 0,1 | 0,005 | 0,4 | 0,015 | 0,008 | 0/0,004/0,008 |
| 55/56/57 | 0,1 | 0,005 | 0,4 | 0 | 0 | 0/0,004/0,008 |
| 58/59/60 | 0,1 | 0,005 | 0,4 | 0 | 0,004 | 0/0,004/0,008 |
| 61/62/63 | 0,1 | 0,005 | 0,4 | 0 | 0,008 | 0/0,004/0,008 |
| 64/65/66 | 0,1 | 0,005 | 0,4 | 0,015 | 0 | 0/0,004/0,008 |
| 67/68/69 | 0,1 | 0,005 | 0,4 | 0,015 | 0,004 | 0/0,004/0,008 |
| 70/71/72 | 0,1 | 0,005 | 0,1 | 0,015 | 0,008 | 0/0,004/0,008 |
| 73/74/75 | 0,4 | 0 | 0,1 | 0 | 0 | 0/0,004/0,008 |
| 76/77/78 | 0,4 | 0 | 0,1 | 0 | 0,004 | 0/0,004/0,008 |

| Variants numbers | *fp* | *wp* [m] | *fs* | *kl* [m] | *wb*1[m] | *wb*2[m] |
|---|---|---|---|---|---|---|
| 79/80/81 | 0,4 | 0 | 0,1 | 0 | 0,008 | 0/0,004/0,008 |
| 82/83/84 | 0,4 | 0 | 0,1 | 0,015 | 0 | 0/0,004/0,008 |
| 85/86/87 | 0,4 | 0 | 0,1 | 0,015 | 0,004 | 0/0,004/0,008 |
| 88/89/90 | 0,4 | 0 | 0,1 | 0,015 | 0,008 | 0/0,004/0,008 |
| 91/92/93 | 0,4 | 0 | 0,4 | 0 | 0 | 0/0,004/0,008 |
| 94/95/96 | 0,4 | 0 | 0,4 | 0 | 0,004 | 0/0,004/0,008 |
| 97/98/99 | 0,4 | 0 | 0,4 | 0 | 0,008 | 0/0,004/0,008 |
| 100/101/102 | 0,4 | 0 | 0,4 | 0,015 | 0 | 0/0,004/0,008 |
| 103/104/105 | 0,4 | 0 | 0,4 | 0,015 | 0,004 | 0/0,004/0,008 |
| 106/107/108 | 0,4 | 0 | 0,4 | 0,015 | 0,008 | 0/0,004/0,008 |
| 109/110/111 | 0,4 | 0,005 | 0,1 | 0 | 0 | 0/0,004/0,008 |
| 112/113/114 | 0,4 | 0,005 | 0,1 | 0 | 0,004 | 0/0,004/0,008 |
| 115/116/117 | 0,4 | 0,005 | 0,1 | 0 | 0,008 | 0/0,004/0,008 |
| 118/119/120 | 0,4 | 0,005 | 0,1 | 0,015 | 0 | 0/0,004/0,008 |
| 121/122/123 | 0,4 | 0,005 | 0,1 | 0,015 | 0,004 | 0/0,004/0,008 |
| 124/125/126 | 0,4 | 0,005 | 0,1 | 0,015 | 0,008 | 0/0,004/0,008 |
| 127/128/129 | 0,4 | 0,005 | 0,4 | 0 | 0 | 0/0,004/0,008 |
| 130/131/132 | 0,4 | 0,005 | 0,4 | 0 | 0,004 | 0/0,004/0,008 |
| 133/134/135 | 0,4 | 0,005 | 0,4 | 0 | 0,008 | 0/0,004/0,008 |
| 136/137/138 | 0,4 | 0,005 | 0,4 | 0,015 | 0 | 0/0,004/0,008 |
| 139/140/141 | 0,4 | 0,005 | 0,4 | 0,015 | 0,004 | 0/0,004/0,008 |
| 142/143/144 | 0,4 | 0,005 | 0,4 | 0,015 | 0,008 | 0/0,004/0,008 |

According to these options, the dynamics of the gondola car in the empty state were calculated by computer simulation. The comparative analysis of the received results is carried out on the combined indicator of stability from derailing of the gondola car $k_{dr0}$, which was calculated as the smallest of the minimum values derailment stability margin coefficients $k_{dr1}$, $k_{dr2}$, $k_{dr3}$, $k_{dr4}$ respectively for each wheelset (min min). Fig. 3 shows the values of the combined coefficient of resistance to derailing $k_{dr0}$ at speeds of the gondola 60, 70, 80 and 90 km/h on a straight track section of a satisfactory condition.

At speeds of 60 and 70 km/h, all calculated values of the coefficient $k_{dr0}$ are higher than the allowable level. However, the margin of stability significantly depends on changes in parameters and characteristics of the technical condition of the running gears. For example, as obtained in the calculation variants 82-90 and 100-108, the exceeding of the wedges worsens the situation with derailing of the gondola only in combination with excessive friction in both central bearing nodes and on side bearings.

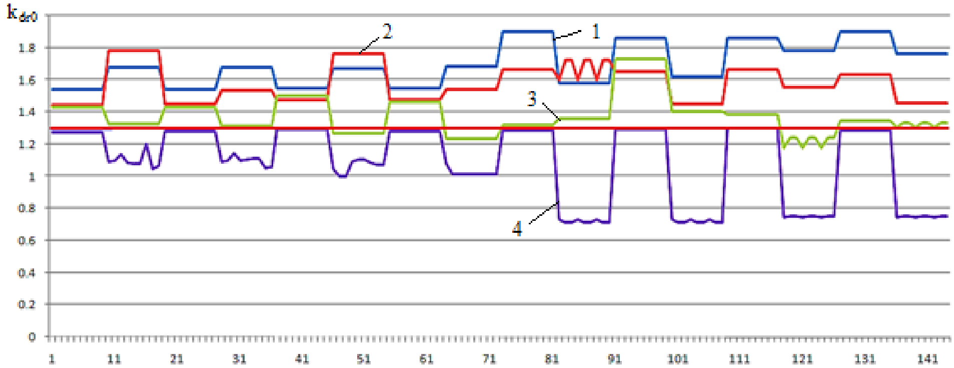


Fig. 3. Combined stability margin indicator $k_{dr0}$ for all calculation options (curves 1, 2, 3, 4 correspond to the values $V$ = 60, 70, 80, 90 km/h)

At a speed of 80 km/h, there is a depletion of stability margin in variants with a combination of three factors: increased friction and longitudinal wear in the central bearing nodes, along with exceeding of the wedges (variants 64-72, 118-126). For other calculation options, the obtained values of the coefficient $k_{dr0}$ are above the maximum allowable level.
According to the results of calculations at $V$ = 90 km/h it turns out that, depending on the options for a combination of factors, the values of $k_{dr0}$ are either on the verge of permissible, or significantly lower. So, in the calculated variants corresponding to cases of movement of the gondola car with the excluded dampers of fluctuations (10-18, 28-36, 46-54, 64-72, 82-90, 100-108, 117-126, 136-144), gained values of $k_{dr0}$ almost two times lower the permissible level when the wedge system is in good condition (1-9, 19-27, 37-45, 55-63, 73-81,91-99,109-117, 127-135). Thus, at a speed of 90 km/h, the situation of derailing the gondola becomes possible with a high degree of probability.

### 3.2. Stability of cars of different types in a rail track

Calculations for gondola car, covered car, hopper car and tank car were performed to determine the effect on the stability of the freight car type. In this case, given the fact that the clearances in the longitudinal direction between the axle boxes and side frames affected the resistance to the derailment of the empty gondola less than other changes in the technical condition, only 16 options were considered calculating the numbers $N = 5 + 9i$, where $i = 1…15$ (Table 3). Fig. 4 and 5 show the values of the combined coefficients of stability $k_{dr0}$ for four types of freight cars in the empty state at speeds of 60 and 80 km/h, respectively. Here the lines connecting the calculated values $k_{dr0}$ are marked as follows: 1 – for gondola car; 2 – for covered car; 3 – for the hopper car; 4 – for the tank car.

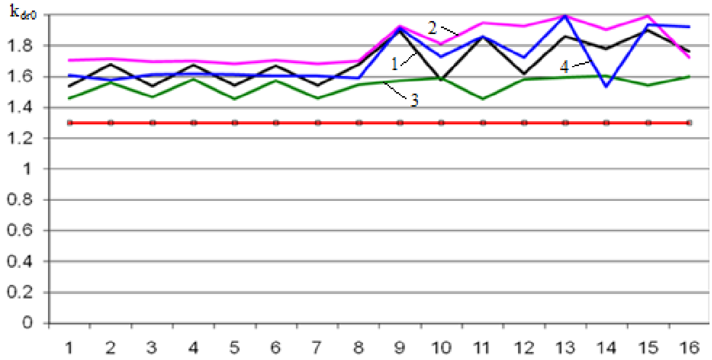


Fig. 4. The value of stability margin indicator $k_{dr0}$ at $V$ = 60 km/h

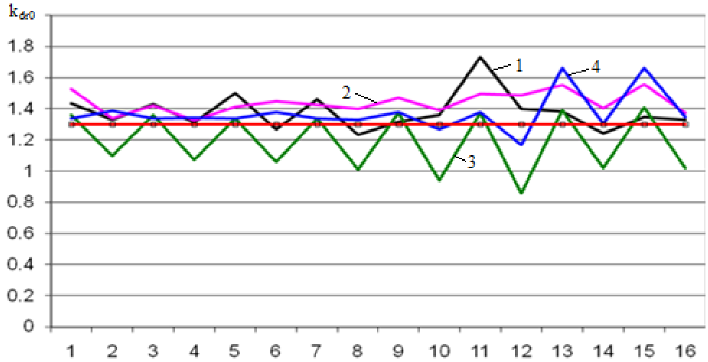


Fig. 5. The value of stability margin indicator $k_{dr0}$ at $V$ = 80 km/h

According to Fig. 4 data the stability margin level from derailing at a speed of 60 km/h for the specified types of freight cars is higher than the allowable value for all considered options. The covered wagon has preferably the best values of the stability margin, while the lowest values of $k_{dr0}$ are obtained for the hopper car. In general, a greater influence of the technical condition of the bogies on the margin of safety is observed for gondola car and hopper car, at the same time, the increase in friction in cantral bearing nodes is reflected in the values of $k_{dr0}$ for the covered car and the tank car.
According to the calculated data (Fig. 5) it turns out that at a speed of 80 km/h the values of the coefficients $k_{dr0}$ are above the permissible value has only a covered car, and for options 14 and 32 (Table 3) the level of $k_{dr0}$ values for a covered car is almost coincides with the allowable value. Depending on the design option for the condition of the running gears of the gondola car and tank car have a margin of stability from derailment or above the allowable value, or slightly below it. The safety margin of the hopper car for almost all variants is below the allowable level, and the technical condition of the running gears significantly affects the $k_{dr0}$ value, changing it from 1.4 for variants with a working wedge system to 0.86 when the wedges are off (free).
According to the relevant calculations, the level of $k_{dr0}$ values, obtained at a speed of 90 km/h for cars of the considered types below the allowable value for almost all calculated options. Especially low values of $k_{dr0}$ were obtained for gondola car and covered car in variants when the increased friction in central bearing nodes and inoperable wedge system were simulated.

## 4. Conclusions

From the analysis of the results of computer-simulated studies of the derailment resistance of freight cars in the empty state, the conclusions are the following:
1. The dynamic phenomena that contribute to the threat of rolling wheels on the rails heads with the subsequent derailing of the wheelsets of freight cars, should include resonant modes, when at certain speeds in the operating range the least defects on the rolling surfaces of the wheels lead to intense vertical oscillations until the wheels are completely unloaded. Depending on the condition of the wedge system and the wear of the wheel rims, resonant (critical) speeds are in a fairly wide range of velocities - from 32 km/h to 82 km/h;
2. To ensure adequate display of the technical condition of the car as the initial data in the dynamic model, the parameters characterizing the deviation from the running gears normal technical condition are selected. The significance of the considered factors is established by means of the factor analysis of cars stability margin indicators. In particular, it is determined that the most dangerous in terms of the empty car in the track stability loss is the exceeding of the vibration dampers wedges;
3. The proposed procedure of reproduction by computer simulation of the situation related to the freight car derailment provides an opportunity to identify the most likely causes of derailment. This approach will deepen the search for investigations into the causes of traffic accidents and will help increase the reliability of predicted estimates of dynamic indicators of train safety.

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# INCORRECT U-TURNING OF VEHICLES AT INTERSECTIONS WITH TRAFFIC LIGHTS

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## *Abstract:*

*The article describes the problem of incorrect U-turns at intersections with traffic lights. Statistical data on road incidents related to U-turns are presented. Then, the international, Polish and foreign regulations concerning u-turning at intersections with traffic lights were analysed. The situations in which U-turns are allowed or prohibited are presented. The differences in design rules for junctions with U-turns in different countries have been taken into account. A literature review was also carried out that outlined various current U-turns around the world, including the design of turning places, the location of turning points, road safety when turning, and the impact of U-turns on traffic conditions.*
*The further part of the article presents the results of field tests of the U-turn at 6 intersections located in Warsaw. The research was conducted by video observation. The results were broken down by age, gender, place of registration of the vehicle, type of vehicle, and the effect of incorrect turning. Data on road incidents at the examined intersections were also analysed. Data from the database kept by the Police were compared with the measurement data. A regression analysis was performed between the types of recorded incorrect manoeuvres and the number of accidents at the intersection. The results of statistical analysis carried out do not indicate the existence of a relationship between the number of identified incorrect U-turns and the number of road incidents at intersections.*
*Based on the research, it was found that the phenomenon of incorrect U-turns at intersections with traffic lights is common, and the use of directional (protected) signals does not eliminate this phenomenon. The conclusions indicate practical solutions to reduce the number of illegally U-turning vehicles. The recommended actions are related to the stage of shaping the road network, designing the road geometry and organizing traffic and traffic lights, and auditing road safety, as well as the stage of road operation.*

***Keywords:*** *U-turning, turning back, traffic signals, traffic lights, road safety*

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## 1. Introduction

Observations of road traffic on the streets of Warsaw show that despite improvements in traffic organization, modernization of traffic signals at intersections, and improvement in road safety, a large number of traffic accidents and collisions can still be observed, caused by the inappropriate, often illegal behaviour of traffic participants. The issue of road safety is related to many aspects of transport. The topic is important because road accidents not only have a direct impact on their victims but also on the travel times and operating costs of vehicle fleets (Rudyk et al., 2019). In the case of motor vehicle drivers, the problem of illegal U-turning can be observed. Data obtained from the Accident and Collision Recording System show that in 2010-2019, the number of accidents related to illegal turning in Warsaw oscillates around 100 events (SEWIK, 2020). Approximately 20-30% of these accidents occur at intersections with traffic lights operating in the three-colour mode. With non-functioning traffic lights, a maximum of one event per year is recorded. The statistics do not indicate significant changes in the number of accidents from month to month. However, variability within the week is noticeable - the number of accidents on Saturdays is about 1/4 less than on weekdays, and on Sundays, the number of accidents drops by half compared to weekdays.

When analysing the problem of inappropriate vehicle U-turning in prohibited places, the high traffic volume in Warsaw, the lack of places where this manoeuvre can be performed safely, as well as the drivers' lack of respect (and often knowledge) of traffic regulations can be identified as the cause of this problem. The phenomenon of lack of knowledge of the rules or even deliberate violation of them is often overlooked during analyses related to the causes of drivers' behaviour (Muslim et al., 2018). Therefore, the need for empirical research related to drivers' incorrect U-turning was identified.

## 2. Literature review

### 2.1. U-Turning rules in legislation

The current road traffic regulations are contained in (MI, 2002), in (Sejm RP, 2012) and international regulations - (CoRT, 1968) and (CoRSaS, 1968). In turn, (MI, 2003) provides guidelines on the use of appropriate horizontal and vertical signage, types of traffic signals placed at intersections and road traffic safety devices.

The Vienna Convention on Road Traffic (CoRT, 1968) is an international treaty in force in the countries which are its signatories. It defines general rules for the movement of vehicles, their equipment, their interaction with pedestrians and cyclists. U-turning is covered only by one provision, indicating prohibition of this manoeuvre on a motorway. The Vienna Convention on Road Signs and Signals (CoRSaS, 1968) only defines the sign prohibiting a U-turn and does not refer to the admissibility of U-turns at intersections.

In Poland, if there are no signs on the road or intersection, U-turning on the road or intersection is permitted. The manoeuvre of U-turning is not forbidden, also when signs are placed on the intersection: F-10, F-11, even if the possibility of U-turning is not indicated on them (a left turn permit is enough). Horizontal signs allowing to perform a U-turn at the intersection, with general signals at the intersection approach, are signs: P-8b, P-8c, P-8e, P-8g, P-8h, P-8i. U-turning is allowed only from the inner lane unless signs indicate that this manoeuvre may be executed from more than one lane. At intersections controlled by traffic lights, the U-turning manoeuvre is possible when the following signals are present: S-1, S-2, and S-3, but only with the arrow symbol for U-turning or U-turning and turning left (Fig. 1).

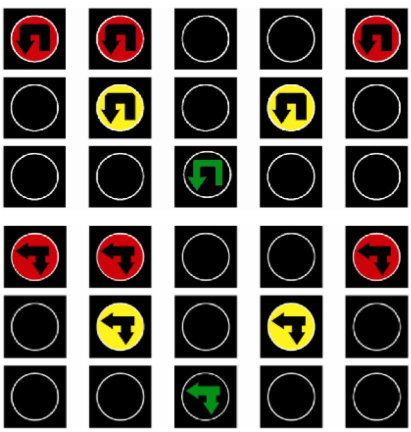

Fig. 1. S-3 turn signals, own elaboration based on (MI, 2003)

The prohibition of U-turning may be introduced by vertical signs, horizontal signs and traffic lights (MI, 2002, 2003). Vertical signs prohibiting the manoeuvre of U-turning at an intersection are prohibition signs: B-21, B-23 and order signs: C-1, C-2, C-3, C-4, C-5, C-6, C-7, C-8. Road surface markings prohibiting U-turning on roads and intersections are: P-2a, P-2b, P-3a, P-3b, P-4. At intersections controlled by traffic lights, the U-turning manoeuvre is not possible when there are S-3 directional signals that do not directly indicate the possibility of U-turning, including signals intended for left-turning drivers (Fig. 2).

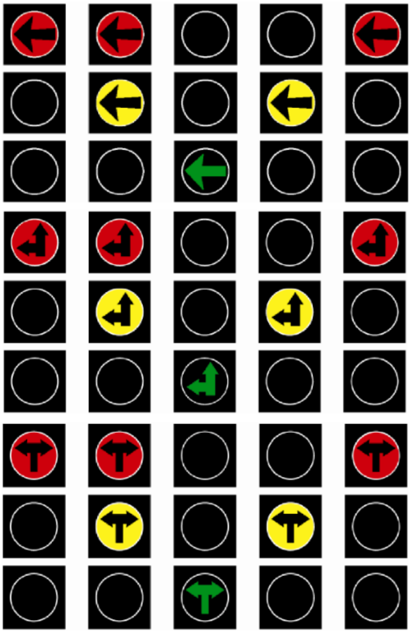

Fig. 2. S-3 directional signal heads prohibiting a U-turn but allowing a left turn, own elaboration based on (MI, 2003)

Particularly little known among drivers is the provision prohibiting U-turning when there is an S-3 signal for left turn only. Drivers often turn in such places without being aware that traffic may be turning simultaneously from the perpendicular approach of the approach they are on.
Foreign regulations contain different provisions for U-turning at intersections with signalling. German regulations (RiLSA, 2015) recommend designating turning areas in the lane dividing the carriageways outside intersections to improve the effectiveness of traffic control and specify situations in which traffic lights should be used at such locations. On the other hand, Russian regulations (NII Avtomobil'nogo Transporta, 2017) allow the existence of conflicting turning vehicles at traffic lights if the traffic volume in the U-turning vehicle stream does not exceed 300 vehicles/hour or the pedestrian traffic volume at the conflicting pedestrian crossing does not exceed 300 persons/hour. In contrast, the Swedish guidelines (Vägar och gators utformning Trafiksignaler, 2012) recommend, to improve the safety of the turning manoeuvre, the use of traffic lights for turning left (which prohibits this manoeuvre in Poland). The use of such traffic lights is mandatory at speeds above 50 km/h. The approach to the problem described in the article is therefore different in different countries.

### 2.2. U-turning literature and research review

The literature on U-turning indicates several directions for current research. The first area of research is the capacity analyses of U-turning places, both traffic signal controlled and unsignalled. These studies are conducted for turning places designated by a dividing lane outside intersections (Ben-Edigbe, 2016), (Mazaheri et al., 2020). They include the dependence of capacity on road geometry, as well as the analysis of gap acceptance. Other studies include the capacity of turning relationships at intersections with traffic lights (Khaled et al., 2017), (Abuhijleh et al., 2020). The results of these studies indicate the saturation flow values used in the capacity calculations or the correction factors for the calculations.
Another direction of research is to change intersections where U-turning is performed into intersections where this manoeuvre is forbidden and to ensure that it can be performed outside the intersection. The purpose of such changes is to improve traffic conditions and road safety. Research points to several possibilities of implementing such a solution. One of them is to restrict the possibility of exiting a subdivision road to turning right only while leaving the possibility of turning left from the main road. Such an intersection, called "Restricted Crossing U-Turn Intersection" (RCUT) has been described in (FHWA, 2009), where the reduction of delays and number of collision points have been identified as advantages of this solution. It was indicated that this solution can be used at intersections with roads with lower traffic volumes, and there should be a wide dividing lane on the main road. Detailed design principles for such intersections are described in

(FHWA, 2014). Research (Ulak et al., 2020) indicates that it is possible to model the safety of such intersections and analyse geometric solutions (turning place distance) while still at the design stage.
Another direction is the use of an intersection where left-turn relations from the main road and the sub-road are eliminated while leaving the possibility of straight traffic, which is referred to by the term "Median U-Turn Intersection Treatment" (MUTIT) (FHWA, 2007). This is equivalent to the junction known in Poland as a "cigar". When designing such an intersection, it is necessary to analyse geometric alternatives, the location of the intersection, rideability, MOEs, the possible use of traffic lights, road signs (including guide signs) and the impact on road safety. Research in this area focuses on defining criteria for the use of such a solution taking into account its efficiency and geometric parameters (Distefano et al., 2016). There are also studies showing traffic safety at such intersections, using simulation models and the traffic conflict analysis method (Kronprasert, 2020). They show an improvement in traffic safety after using a MUTIT-type intersection, but with an adequate distance between the U-turning places and the intersection with the cross road. Studies on the effectiveness of such intersections equipped with traffic lights (Bared et al., 2002) indicate an overall improvement in traffic conditions, but at the cost of increased delay for U-turning relationships. There has also been researched indicating the feasibility of using non-controlled intersections as U-turning locations and including an evaluation of traffic conditions at such intersections (Fan et al., 2013). The study also showed a solution to improve traffic conditions for turning vehicles by using double U-turning places, separate for light and heavy vehicles. Such a solution can be applied with narrower dividing lanes, but the literature only shows results of simulation studies and no examples of the application of such solutions in practice are known.
A review of foreign literature indicates that there is a tendency to move U-turning places outside the intersection area. This improves traffic conditions for vehicles driving straight ahead (especially on the main road) and improves road safety by replacing dangerous left-turning manoeuvres outside the intersection. Also of importance is the fact that in such a case the driver has an easier task as he has to give way to a smaller number of traffic streams, which is a factor that improves safety (Szczuraszek et al., 2008). The disadvantages of such solutions include poorer legibility of the junction, which requires the use of appropriate guide signs, and increased delays by vehicles performing manoeuvres at the junction. This limits the use of such intersections to situations where roads of clearly different significance in the traffic system intersect.
In Poland, there are few roads with a wide dividing lane. Therefore, the possibility of using MUTIT and RCUT type crossings is limited. There are only a few turning places designated outside intersections. In most cases, these are used to improve the efficiency of traffic control and are placed before the approaches of controlled intersections. For this reason, most U-turning manoeuvres take place at intersections. Intersections in cities were often established as uncontrolled intersections, with the increase in traffic using traffic lights with general signals, and later using directional signals and dedicated phases for left turns.
Traffic safety analyses of U-turning movements are hampered by the fact that accident databases only include accidents at which the police were present. And even for these accidents, the information is often incomplete and does not allow the exact cause of the accident to be determined (Żukowska, 2015). For this reason, indirect measures of road safety - e.g. the number of violations of a given type of regulation or the number of violations causing traffic disruption - can be used for analyses. At the same time, it should be noted that, according to research (Cieśla et al., 2020), the most important determinant of mode choice is travel time, while travel safety is only given sixth place, after the cost or comfort of travel.
Traffic analyses often omit U-turning vehicles because their number at many intersections is small, so turning does not have a very significant impact on intersection traffic - it is omitted from analyses of, for example, pedestrian behaviour (Thakur et al., 2019), cyclists (Cieśla et al., 2018) or left-turning vehicles (Yao et al., 2020). Similarly, studies on traffic control solutions are more general. Studies on timing displays (Sobota et al., 2018) do not often distinguish a separate evaluation of left-turning and turning signal groups, although they tend to have shorter green signal durations and longer waiting times for drivers to wait for the green signal, which may result in different behaviours from those of drivers going straight ahead. Also, among the factors

affecting traffic safety at intersections, no separate factors related to U-turning are identified (Wojtal et al., 2017). Studies on traffic safety refer to RCUT intersections, practically unheard of in Poland (Olearte et al., 2011). Similarly, the impact on traffic safety of removing a controlled intersection and replacing it with a Median U-Turn (MUT) intersection was analysed (Azizi et al., 2013).

## 3. Research fields

Intersections located at various locations in the city of Warsaw, Poland, were taken into consideration to evaluate the U-turning manoeuvre. All intersections used S-3 left-turn signals during the study period, which prohibit turning according to regulations (MI, 2002). Intersections with different geometric layouts and fairly high traffic volumes were selected for the study. Seven intersections were evaluated. The research was conducted in September, October and November 2017.

Intersection No. 1 - the intersection of Przyczółkowa Street with Wilanowska Avenue. The analyzed lane is located on the southern approach of the intersection. There are two lanes designated for left turns, each 3.5 m wide. During the measurements, a fixed-time control was in operation at the intersection.

During the measurements, the conflicting turning traffic was moving from the lane marked with A-7 and P-13 signs. As a result of the non-adjustment of the intersection road signs to the regulations in force at the time (MI, 2003, 2015) and the lack of signalization in the entire area of the intersection, vehicles turning left and illegally U-turning from Przyczółkowa Street were moving simultaneously with vehicles turning right from Wilanowska Avenue. This is a dangerous situation that endangers the safety of road users.

In the period after the measurements were conducted, the traffic lights were modernized and the colliding right-turn relation was controlled with directional signalling devices. In the initial period of operation of this solution, a very high number of conflicts between vehicles illegally U-turning and those turning right were observed. This was also caused by the routing of routes with a turning relationship by the navigation systems. After notifications to the navigation system operator, made among others by one of the authors of the article, routes including turning at this intersection were no longer determined.

Intersection No. 2 - Czerniakowska Street intersection with Gagarina Street and Nehru Street. Czerniakowska Street is a dual carriageway road with four lanes in each direction. The analysed road section is located on the northern approach of the intersection. The width of the traffic lane for turning left is 3.5 m. Vehicles turning left and illegally U-turning from Czerniakowska Street receive the green signal simultaneously with vehicles from this intersection driving straight ahead. Illegal U-turning is made difficult due to the queues of vehicles behind the intersection in the northbound direction. Due to the queues in front of the pedestrian crossing, drivers performing a turning manoeuvre stop in the middle of the intersection, impeding the movement of other vehicles, mainly those coming straight from Nehru Street. After the measurements were conducted, the traffic organization and the method of signal system control were changed at the intersection in connection with the construction of Polski Walczącej Avenue.

Intersection No. 3 - the intersection of Rolna Street with Niedźwiedzia Street. The analysed lane is located at the southern approach of the intersection. The lane width for the left turn is 3.5 m. Actuated control operates at the intersection. Vehicles turning left and illegally turning from Rolna Street have the green signal simultaneously with vehicles from the same approach going straight ahead. It has been observed that during one traffic light cycle, approximately three cars may turn left. During the tests, there was a large queue of vehicles, which caused many cars to pass on the yellow and red signal.

Intersection No. 4 - the intersection of Wolska Street with Sowińskiego Street. The intersection is four-leg. Wolska Street is a dual carriageway road with three traffic lanes in each direction, separated by a narrow dividing lane. In the area of the intersection, an additional lane for turning left has been introduced. The width of the traffic lane for turning left is 2.75 m.

Actuated control is used at the junction. Vehicles turning left and illegally U-turning from Wolska Street have the green signal simultaneously with vehicles from the same approach which are driving straight ahead and with vehicles from Sowińskiego Street, which have the signal for turning right displayed at that time. At the analysed intersection, vehicles were observed turning right from the southern

approach on a displayed yellow signal and in the initial seconds of a red signal. This situation may lead to traffic accidents with vehicles illegally U-turning from the north-eastern approach.
Intersection No. 5 - the intersection of Gandhi Street with KEN Avenue. The analysed lane is located on the south-western approach of the intersection. The lane width for turning left is 2.75 m. Actuated control operates at the intersection, adjusting the length of displayed signals for given groups depending on traffic conditions. Vehicles turning left and illegally U-turning from Gandhi Street have the green signal simultaneously with vehicles from the same street from the opposite approach turning left. After the measurements were made, the traffic lights were upgraded and an S-3 directional signal allowing left turns and U-turns were installed on the approach covered by the measurements.
Intersection No. 6 - The intersection of Wilanowska Avenue with Rolna Street and Bukowińska Street. The analyzed lane is located on the south-east approach of the intersection. The width of the traffic lane for left turns is 3 meters. Actuated control operates at the intersection. Vehicles turning left and illegally turning from Wilanowska Avenue receive the green signal simultaneously with vehicles from Rolna Street, which receive the displayed signal for turning right.
Intersection No. 7 - The intersection of Żwirki i Wigury Street with Pruszkowska Street. The analyzed lane is located on the southern approach of the intersection. The width of the lane for turning left is 3 m. Actuated control is used at the intersection. Vehicles turning left and illegally turning back receive the signal simultaneously with vehicles from the same approach going straight ahead and vehicles from Pruszkowska Street, which at the time display the signal for turning right.

## 4. Research method

The research was carried out using a Panasonic Lumix camera. From the observation point, the drivers' behaviour at the observed intersection was recorded. The recordings from the camera allowed for a more in-depth analysis of the method and consequences of turning. The measurements were made in a way that was unnoticeable for the road users. This allowed eliminating the behaviour of drivers, whose actions could be changed during the observation.
The tests were carried out at different times and on different days of the week. The minimum sample size for which conclusions could be drawn was set as 25 turning vehicles for one measuring point. To obtain as many turning drivers as possible, measurements were made for 1.5 hours at each intersection. According to research (Hadi et al., 1995), 45% of traffic accidents at urban intersections were caused by heavy traffic. For this reason, the surveys were usually carried out during the morning or afternoon rush hours. The measurements were carried out during rain-free days in September, October and November 2017.
Driving behaviour is influenced by many factors, related to the current traffic situation and directly to the driver, including the driver's gender, age, familiarity with the infrastructure they are on and the purpose of driving, the need to hurry, habits (Fuller et al., 2002). During the measurements taken, the turning drivers were classified into different categories such as the type of vehicle, the place of registration of the vehicle they were driving, the gender and age of the driver and the presence of a passenger.
In the category of the type of vehicle driven, a distinction was made between passenger cars, heavy vehicles (vans, trucks, buses) and single-track vehicles. Based on the number plates, vehicles were divided into three categories: registered in Warsaw, registered up to 30 km from Warsaw, and registered more than 30 km from Warsaw.
The surveyed drivers were also divided into men and women. In the driver age category, three age ranges have been established, based on estimations only. These are 18-30 year-olds, 31-50 year-olds and 51+ year-olds.

## 5. Research findings

### 5.1. Results of fieldwork

Surveys were conducted and observation sheets completed for all locations. Overall, the number of incorrect U-turns during the 1.5 hours of observation at each location is shown in Table 1.

Table 1. Number of illegal U-turners at intersections

| Intersection | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Number of illegal U-turns | 79 | 61 | 25 | 94 | 46 | 53 | 47 |

The behaviour of drivers U-turning inappropriately at individual intersections was analysed in depth.

The paper presents a comparative analysis of the results of measurements at individual intersections. Summary results of measurements at all intersections are presented in Table 2. Abbreviations used in Table 2 mean: RP - vehicle type (SO - a passenger car, PC - heavy vehicle, PJ - single-track vehicle); MRP - a place of vehicle registration (1- registration in Warsaw, 2 - registration up to 30 km from Warsaw, 3 - registration over 30 km from Warsaw); PK - gender of the driver (K - women, M - men); WK - age of the driver (1 - 18-30 years, 2 - 31-50 years, 3 - over 51 years).

Table 2. Aggregate results of measurements at all intersections

| Intersection | Intersection Results by category in [%] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | RP | | | MRP | | | PK | | WK | | |
| | SO | PC | PJ | 1 | 2 | 3 | K | M | 1 | 2 | 3 |
| 1 | 99 | 1 | 0 | 72 | 11 | 17 | 39 | 61 | 27 | 61 | 12 |
| 2 | 89 | 3 | 8 | 77 | 8 | 15 | 27 | 73 | 34 | 41 | 25 |
| 3 | 92 | 8 | 0 | 84 | 4 | 12 | 32 | 68 | 20 | 44 | 36 |
| 4 | 96 | 2 | 2 | 63 | 17 | 20 | 30 | 70 | 31 | 57 | 12 |
| 5 | 100 | 0 | 0 | 76 | 15 | 9 | 41 | 59 | 37 | 41 | 22 |
| 6 | 89 | 9 | 2 | 78 | 9 | 13 | 34 | 66 | 28 | 58 | 14 |
| 7 | 85 | 11 | 4 | 68 | 19 | 13 | 34 | 66 | 19 | 51 | 30 |

The table shows that the most common vehicle was a passenger car. It was noted that those turning with a heavy vehicle would have difficulty manoeuvring due to the geometry of the intersection. This could be due to the large dimensions, large turning radius and low dynamic capabilities of the car.

When analysing the percentage share of turning drivers in relation to the place of vehicle registration, the highest number of recorded vehicles was registered in Warsaw.

At each studied intersection, the percentage share of women was significantly lower than that of men. At each intersection, the most numerous age group was between 31 and 50 years old.

When measurements were made at different intersections, different effects of turning were detailed. To obtain a comparative analysis of the intersections, Table 3 shows the effects of turning at unauthorised places for each intersection.

The effects of turning were defined as follows: A - passing safely without forcing priority on another traffic participant, B - forcing another driver to reduce speed slightly, C - forcing another driver to reduce speed significantly, D - forcing another driver to stop at the intersection, E - running into the kerb.

Table 3. The effects of U-turning at intersections

| Intersection | Effects of U-turning [%] | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| 1 | 91 | 4 | 1 | 4 | 0 |
| 2 | 94 | 4 | 0 | 2 | 0 |
| 3 | 64 | 4 | 12 | 0 | 20 |
| 4 | 81 | 4 | 11 | 4 | 0 |
| 5 | 76 | 10 | 14 | 0 | 0 |
| 6 | 70 | 18 | 10 | 2 | 0 |
| 7 | 69 | 23 | 6 | 2 | 0 |

Based on Table 3, graphs were created (Figure 3 and Figure 4), taking into account only the negative effects caused by illegal U-turning. Based on the data from the graphs, it is possible to identify the locations where drivers most frequently disrupted the flow of traffic. Intersection 3 recorded the highest proportion of negative impacts of illegal U-turning. Drivers were mainly entered on the kerb and forcing other road users to significantly reduce their speed. The reason for such a bad result may be the prohibition of turning at 1.7 km before the intersection and the geometry of the intersection, mainly the radius and width of the island dividing the carriageways. Intersection No. 7 had the highest percentage of people who forced another traffic user to slightly reduce speed. Among the observed intersections, the largest number of people forced a significant change in speed at intersection No. 5. The main reason for this phenomenon was that they performed the turning manoeuvre too slowly.

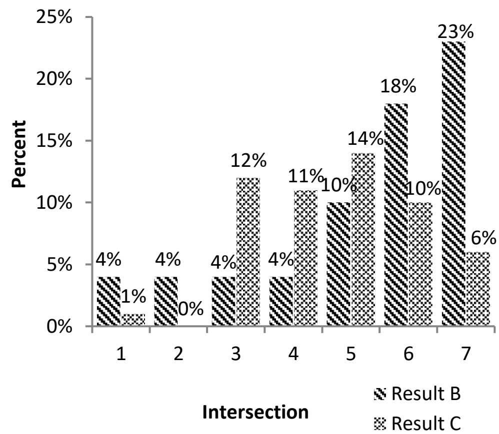


Fig. 3. The percentage share of U-turners according to the effect of turning back depending on the crossroads part 1

Intersections No. 1 and No. 4 had the highest number of people who forced other drivers to stop their vehicle completely. In the first location, this was due to a lack of awareness of the priority at the given intersection. At the second one, it was due to waiting too long before carrying out the turning manoeuvre, which resulted in the signal being changed to prohibit entering the intersection. It can be deduced from the observations that there is a variation in the effects of the U-turning manoeuvre at different intersections.

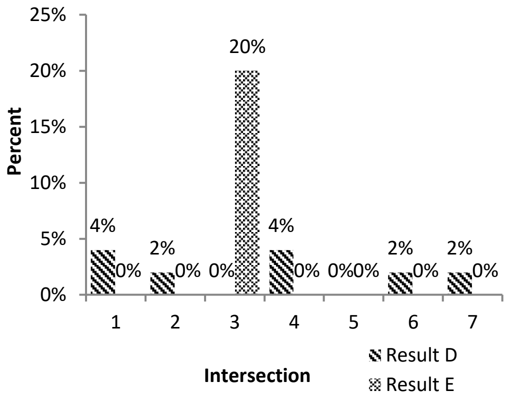


Fig. 4. The percentage share of U-turners according to the effect of turning back depending on the crossroads part 2

For all measurement points, a summary of the occurring effects of U-turning (A - safe passage, B - disruption of traffic flow) depending on the gender of the driver was created (Table 4).

Table 4. Percentage of U-turners according to the sex of the driver and the effect of U-turning at intersections

| Intersection | Number of U-turners according to the sex of the driver and the effect of the crossing [%] | | | |
|---|---|---|---|---|
| | Female | | Male | |
| | A | B | A | B |
| 1 | 87 | 13 | 94 | 6 |
| 2 | 94 | 6 | 95 | 5 |
| 3 | 75 | 25 | 59 | 41 |
| 4 | 83 | 17 | 78 | 22 |
| 5 | 88 | 13 | 70 | 30 |
| 6 | 61 | 39 | 74 | 26 |
| 7 | 81 | 19 | 61 | 39 |

Based on Table 4, graphs were created (Fig. 5, Fig. 6). depicting the percentage of female and male U-turners depending on the intersection.
Based on the graphs in Figures 5 and Figure 6, it is possible to compare the effects of U-turning among women and men at different intersections. The greatest discrepancies in negative impacts can be observed at intersections #3 (a greater proportion of negative impacts among males), #5 (a greater proportion of negative impacts among males), #6 (a greater proportion of negative impacts among females), and intersection #7 (a greater proportion of negative impacts among males). At the remaining intersections, the differences are less than 10%.

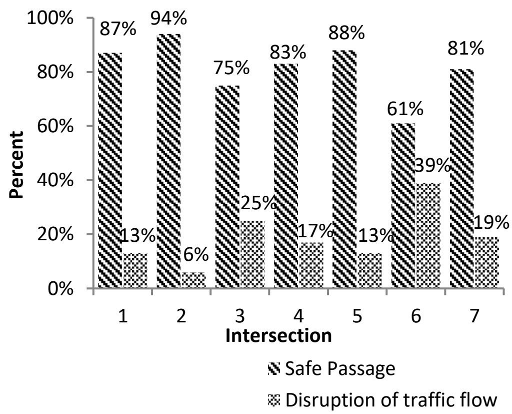


Fig. 5. Percentage of women turning back depending on the intersection

The persons who turned back more often at the selected measurement points were men. Based on the study, it can be concluded that they more often negatively affected the traffic flow while manoeuvring. On this basis, it can be concluded that the driver's gender has an influence on turning in a prohibited place.
Table 5 shows the summary results for the number of turning drivers by age range and the effect of the manoeuvre at the different measurement points (A - safe crossing, B - disruption to traffic flow).
Analysis of the data shows that intersection #7 recorded the highest number of negative U-turning impacts for 18 to 30-year-olds. Within this age range, the highest number of turning drivers who safely crossed the intersection was recorded at intersection 2, with all negative impacts involving forcing another road user to slightly change speed.

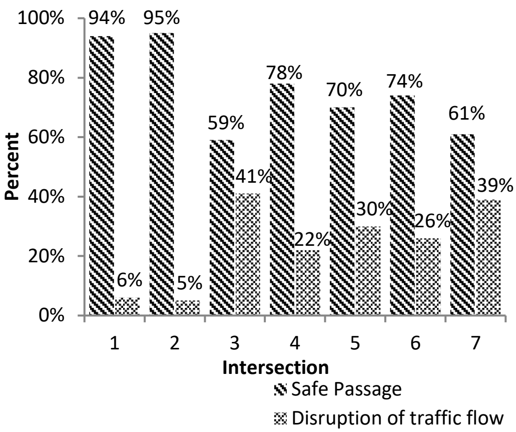


Fig. 6. Percentage of men turning back depending on the intersection

Table 5. Percentage of U-turners according to the age of the driver and the effect of turning back at junctions

| Intersection | Number of U-turners according to the age of the driver and the effect of the crossing [%] | | | | | |
|---|---|---|---|---|---|---|
| | 18-30 | | 31-50 | | 51+ | |
| | A | B | A | B | A | B |
| 1 | 91 | 9 | 89 | 11 | 100 | 0 |
| 2 | 95 | 5 | 100 | 0 | 87 | 13 |
| 3 | 80 | 20 | 10 | 0 | 50 | 50 |
| 4 | 72 | 28 | 85 | 15 | 73 | 27 |
| 5 | 87.5 | 12.5 | 75 | 25 | 60 | 40 |
| 6 | 73 | 27 | 65 | 35 | 86 | 14 |
| 7 | 56 | 44 | 67 | 33 | 86 | 14 |

Drivers between the ages of 31 and 50 were the most common group among those surveyed. At the two measurement points, 100% of the U-turning drivers passed safely, without obstructing other drivers. The overall share of drivers who more or less disrupted the traffic flow in this age category was 17%. This is the best result among the surveyed age groups.
At intersection No. 3, the highest share of cases of performing a U-turning manoeuvre in a way that impeded the traffic flow of other vehicles was noted. Such behaviour constitutes as much as 50% of all recorded situations. Among all age groups, the overall percentage of negative consequences of turning is the highest for adults over 51 years old.
Based on conducted measurements, it cannot be unambiguously determined which drivers in which age bracket cause most traffic obstructions at selected intersections. Different percentages of individual consequences of an improper manoeuvre were recorded at the measurement points. Based on the presented data, it may be concluded that the age bracket of drivers does not influence the decision to perform a U-turn.

### 5.2. Analysis of traffic accident data

The analysis of traffic accidents related to wrong U-turning in 2017 in Warsaw showed that 105 accidents took place in this period. Only one location has a significantly higher number of accidents of this type as many as 7. This is Górczewska Street, in the vicinity of the Wola Park Shopping Centre. In this place in that period was introduced temporary traffic organization associated with the construction of the second line of the underground. At the remaining intersections no more than 1 accident caused by an incorrect U-turn was observed. This gives rise to a suspicion that these accidents are qualified as other accidents including side events.
Traffic accident statistics for 2017 were analysed for the intersections included in the analysis. The number of traffic accidents at each intersection is shown in Table 6.

Table 6. Traffic accidents at analysed intersections

| Intersection | Number of accidents in 2017 | Number of side crashes in 2017 |
|---|---|---|
| 1 | 9 | 1 |
| 2 | 18 | 3 |
| 3 | 2 | 0 |
| 4 | 7 | 2 |
| 5 | 0 | 0 |
| 6 | 7 | 3 |
| 7 | 1 | 0 |

There are numerous rear-end crashes at intersections that are unrelated to U-turning and lateral crashes related to lane changes, which were omitted from the analysis and are not shown in Table 6. The SEWiK database does not contain detailed information on accidents, so it is impossible to link a given accident to an intersection approach, and accidents classified as sideswipe accidents may occur in different situations and locations at the intersection.
However, statistical analysis was carried out by determining Pearson and Spearman correlation coefficients between the measured numbers of misbehaviour, speeding violations, stopping violations, total

priority violations and the number of traffic accidents or the number of side crashes. No statistically significant relationship was found in any of the cases. Various regression functions were determined using tools for selecting the best regression function, e.g. linear regression, LOESS regression (Long et al., 2019). It was found that in each case of regression between the values, the coefficients have a very wide confidence interval at the level of 0.95, practically in the whole length reaching or crossing the horizontal axis. Example plots for the number of events and the number of side crashes versus the number of violations are shown in Figures 7 and 8.

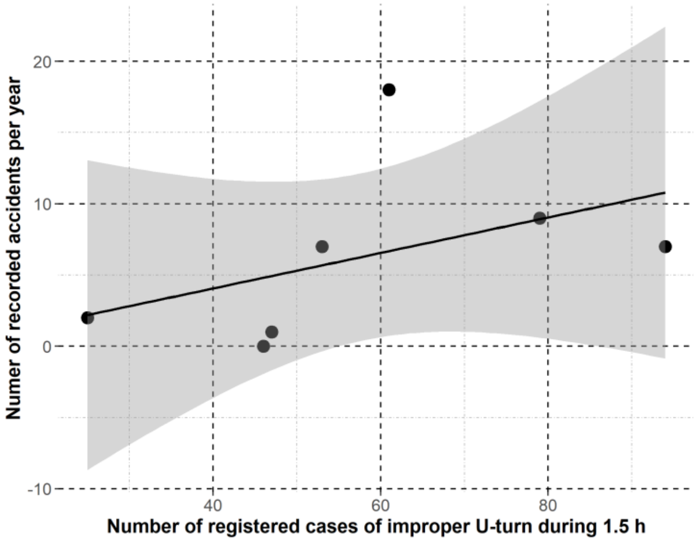


Fig. 7. Number of accidents with 0,95 confidence interval

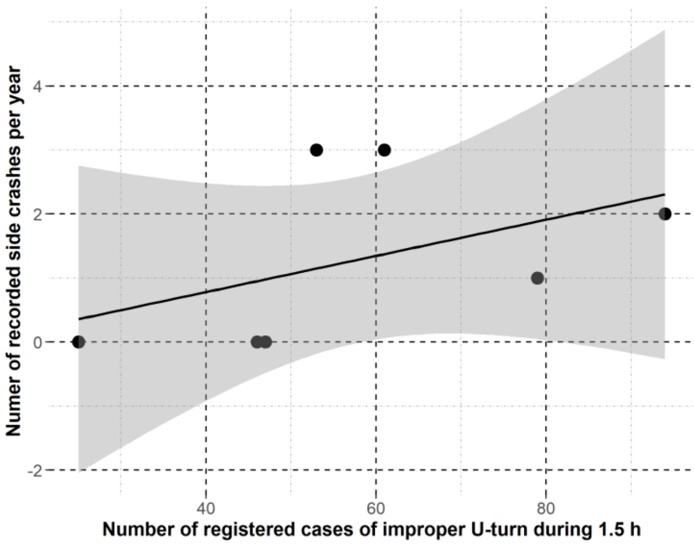


Fig. 8. Number of side crashes with 0,95 confidence interval

For the number of traffic accidents and the number of side crashes, multivariate linear regression was performed between the number of speed reduction enforcements, stopping enforcements and kerb invasions. The results of the analysis are presented in Tables 7 and 8.
The estimated values of all coefficients close to zero, with a very large standard deviation, a high probability Pr and a wide confidence interval, indicating that the model variables do not significantly affect the number of events and the number of side crashes. Analogous conclusions for the whole can be drawn by analysing the $R^2$ coefficient of 0.5678 for the number of events and 0.2565 for the number of side crashes and the p-value of 0.414 and 0.7973, respectively.
The conducted analysis did not show any relationship between indirect measures of road traffic safety and the number of traffic accidents at the analysed intersections. Therefore, it is not possible to forecast direct measures of road traffic safety based on the results of the conducted measurements. Another problem identified during the analysis is a small number of accidents with police participation in their elimination, and only such accidents are included in the SEWiK database, as well as a small scope of data included in the SEWiK database.

## 6. Summary and conclusions

Based on the conducted measurements, it may be stated that U-turning in prohibited situations is a phenomenon commonly occurring at controlled intersections in Warsaw. On average, 58 drivers U-turned at the analysed intersections during a 1.5-hour observation period. Most cases of illegal turning take place safely, which is due to good visibility and legibility of priority rules and wide exits at most of the analysed intersections. The situation is different in the case of conflicts with vehicles moving on a signal allowing U-turning with the vehicles moving on the right turn on red signal (so-called “green arrow”) from a perpendicular approach - in this case, the visibility is much worse and the priority rules are not clear, as drivers do not know what signal is displayed for the other driver. However, analyses of traffic accidents indicate that the number of recorded traffic accidents at the analysed intersections is not significant and is not statistically significantly related to the recorded irregularities while U-turning.
The main conclusion that can be drawn from the research is that the use of an S-3 directional signal allowing only left turns is not an effective means of ensuring the elimination of illegal U-turning at the intersection. The reason for this situation is the widespread lack of knowledge of the provision prohibiting U-turning in such a situation.

Table 7. Regression model analysis for the number of road accidents

| Variable | Estimate | Std. Error | t value | Pr(>\|t\|) | Confidence interval of the regression coefficient | |
|---|---|---|---|---|---|---|
| | | | | | 2,5% | 97,5% |
| Number of speed reduction forces | -0.78693 | 0.50373 | -1.562 | 0.216 | -2.39002 | 0.81616 |
| Number of Forces to Stop | 0.33841 | 1.89268 | 0.179 | 0.869 | -5.68495 | 6.36176 |
| Number of curbs hits | -0.01379 | 0.37197 | -0.037 | 0.973 | -1.19757 | 1.16999 |

Table 8. Regression model analysis for the number of side crashes

| Variable | Estimate | Std. Error | t value | Pr(>\|t\|) | Confidence interval of the regression coefficient | |
|---|---|---|---|---|---|---|
| | | | | | 2,5% | 97,5% |
| Number of speed reduction forces | -0.03984 | 0.14681 | -0.271 | 0.804 | -5.29283 | 7.91056 |
| Number of Forces to Stop | 0.20143 | 0.55163 | 0.365 | 0.739 | -1.55409 | 1.95695 |
| Number of curbs hits | -0.04154 | 0.10841 | -0.383 | 0.727 | -0.38656 | 0.30348 |

It would be advisable to apply supplementary driver education aimed at maintaining and enriching knowledge of traffic regulations (Szczuraszek, 2008).
Other conclusions concerning particular categories of traffic participants indicate that, although the problem concerns the whole cross-section of the driving population, educational activities should be directed in particular to older male drivers.
The conclusions of the research should also be used at the various stages of the life cycle of road infrastructure. At the stage of traffic planning and forecasting, proper planning of the road network is essential, including the designation of U-turning places. Such places should result from traffic measurements and, in the case of a newly designed road, from traffic forecasts. The possibility of U-turn should not be eliminated at the initial stage of making traffic forecasts to identify places where it is necessary. This, therefore, requires an update of the macroscopic traffic models used to perform forecasts.
At the stage of road design, it is necessary to design the possibility of U-turning at junctions where the traffic of U-turning vehicles is forecast. The surroundings of the road and the possibility of access to facilities located on the road should be analysed. The U-turning should provide adequate rideability. Solutions presented in foreign literature for the design of U-turning places allow the elimination of the phenomenon described in the article. However, these solutions can only be applied at selected intersections, and Polish roads, with narrow dividing lanes, do not allow their widespread use. Nevertheless, during the design of new roads and a thorough reconstruction of existing roads, such a solution may be considered. One of the methods of eliminating U-turning at unauthorised places is to provide an opportunity to safely perform this manoeuvre at designated places. Often U-turning at unauthorised places is caused by the lack of possibility to perform this manoeuvre on a long section before and after an intersection.
During road operation, U-turning at forbidden places can be eliminated by proper drafting of maps used in car navigation systems - it is necessary to eliminate in these maps the relation of U-turning at a place, where it is forbidden in the current traffic organization, although in reality this activity is not performed. U-turns in prohibited locations may be caused by the navigation system's designation of such a route and the driver's reluctance to take a route with a longer travel time. This phenomenon increases especially during periods of congestion on the road network (Juhász et al., 2017).
In cases where illegal turning is the cause of repeated traffic accidents at the operational stage, other traffic organisation measures should be applied, e.g. additional B-23 "No U-turning" signs. Although their use is not formally necessary when an S-3 traffic signal is used for vehicles turning left, it unambiguously prohibits drivers from U-turning at a given place.
It should be noted that even the Road Safety Audit Manual (Podręcznik audytu BRD, 2019) does not provide guidance for evaluating a road for the placement of U-turning areas. In the opinion of the authors, this manual should be supplemented with issues related to U-turning, at each stage of the road safety audit. In particular, the need to pay attention to considering the location of U-turning places in conjunction with the development of the road environment should be emphasised. If on the section between intersections on a dual carriageway there are sources or destinations (including individual exits), there will be the phenomenon of U-turning connected with servicing those facilities, even not complying with the regulations. As such, provision must be made at the design stage for legal U-turning to and from these facilities. The importance of this issue increases as the road safety audit procedure is being extended to non-TEN-T roads in 2021 (Directive (EU) 2019/1936, 2019).
The problem with implementing a U-turn is often the width of the dividing lane (e.g. intersection No. 3), which does not make it possible to ensure passage for all vehicles. In such cases, a solution applied by, among others, the Mobility and Transport Policy Office of the Municipal Office of the Capital City of Warsaw and the General Directorate for National Roads and Motorways (GDDKiA) in Warsaw is the use of the S-3 directional signal device permitting a U-turn and the placement of the B-23 "No U-turn" sign with a label reading "Not for passenger cars and single-track vehicles". It is also possible to additionally widen the road shoulder to ensure passability for long vehicles.
These proposals apply to all types of traffic lights. The issues related to the proper handling of turning movements are dealt with in the earlier design

stages, before the development of the traffic control algorithm. Therefore, once the presented conclusions are taken into account, any control algorithm can be used e.g. (Sathiyaraj et al., 2020), (Zhao et al., 2018), (Lin et al., 2020).
During the operational stage of the road, more frequent traffic police checks are also recommended at intersections where the problem of improper U-turning has been diagnosed. Consistency and punishment of traffic violators should effectively improve road safety. In countries with strict penalties for non-compliance with traffic regulations, drivers are less likely to break them. The best examples of such countries are the USA and Sweden (Szczuraszek, 2008).

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