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EFFICIENCY ASSESSMENT OF MEASURES TO INCREASE SUSTAINABILITY OF THE TRANSPORT SYSTEM

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Abstract. This paper considers managerial approaches to increase efficiency of the urban transport system such as promotion and integration of sustainable modes of transport, development of public transport route network, renewing the existing vehicle fleet and shift to environmental friendly fuel types in the public transport system. To assess such kind of efficiency, it is proposed to take into account the economic viability of suggested solutions as well as their influence on social sphere, environmental friendliness and sustainability of the urban transport system. The city of Naberezhnye Chelny (Russia) was chosen for the case study, where the following measures were modelled: changes of bus route network and choice of an optimal fleet on routes depending on passenger flow by hours of day. In addition, the efficiency of these measures were assessed. To evaluate the sustainability of the proposed route network, the method of "radar map" was used, which shows both strengths and weaknesses of selected indicators. Together with this evaluation, analysis of risks in managing the urban bus transportation was carried out.

Keywords: sustainable transport, transport system efficiency, "radar map", route network, "spider chart", mass passenger public transport.

Notations

CO – carbon monoxide;
CO_2 – carbon dioxide;
C_xH_y – hydrocarbon;
EC – European Commission;
EU – European Union;
EMF – electromagnetic field;
GHG – greenhouse gas;
GPS – global positioning system;
ICT – information and communications technology;
NO_x – nitrogen oxide;
PTS – public transport stop;
SMP – sustainable mobility project;
UITP – International Association of Public Transport (in French: *Union Internationale des Transports Publics*);
UN – United Nations;
WBCSD – World Business Council for Sustainable Development.

Introduction

Rapid urban growth is one of the reasons of different social and economic challenges. The UN predicts that by 2050 around 70% of the world population will live in the cities, which will significantly change the way we live, work, and generally move around. The *TERM 2016* report (EEA 2016) assesses that transport activity across Europe will increase by 40% between 2010 and 2050: the fastest growth is expected in the aviation sector as well as freight transport will grow by 58%. Taking into account this scenario, expected GHG emissions from transport sector will increase to 15% above 1990 levels between 2030 and 2050: this indicator is slightly higher than the proposed by the EU 60% reduction until 2050 as a target. The report points out that transport contributes 25% of the GHG emissions in the EU and is the only large economic sector, where GHG emissions are higher than their levels in the 1990s. At the UN Climate Summit in the year 2014, the UITP launched the *Declaration on Climate Leadership*; its main aim is to push the sector, which must double the market share of public transport by 2025 (UITP 2020). Their commitment must support cities and towns to enhance, to

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accelerate and to ensure the efficiency of urban mobility, as well as, to intensify their efforts, which are directed on preparation for and adaptation to changes of climate.

Since technical solutions alone are not enough to ensure the reduction of environmental impacts from transport, both incremental and transformational changes are necessary to make the population mobility system more sustainable and to meet different environmental goals standing forward the transport sector including decarbonization. Recommended incremental changes include two types of improvements: (1) the fuel efficiency of vehicles and (2) the efficiency of the transport management system on the whole (in general). Proposed transformational changes focus on human consumption, habits, lifestyle choices and their changes with the aim to transform the way how society uses transport: it concerns, for example, to avoid unnecessary trips or to use cycling or walking as modes of transport as well as to introduce and to promote electric and self-driving vehicles. Population car-dependency, continued dependence on fossil-fuel powered internal combustion engines together with large investments in the road transport infrastructure hinder all attempts and efforts to shift towards more sustainable transport.

1. Transport system efficiency is a basis of its sustainability

1.1. Urban transport systems

Each urban space is a complex social, natural and man-made system, which equilibrium guarantees its sustainable development (Figure 1). Environmental pressures are caused mainly by two reasons: the high concentration of people and economical activities in the urban area and insufficiently managed processes of transportation. However, cities can be designed, planned, governed and managed by using increasingly efficient tools and approaches. Together with the mobility development, the urban structure started to be more complex and comprehensive. The role of cities is critical to transit towards a resource-efficient, low-carbon and ecosystem-resilient society. The cities of tomorrow have the great potential to be more healthy, greener and smarter through better and efficient urban planning and governance. Smart urban design has a great influences on transport demand. Local authorities can encourage to use sustainable modes of transport, for example, by providing efficient, accessible and reliable public transport and by organizing convenient cycling and walking infrastructure.

Thus, to support the sustainability of the urban environment, transport planning must take into account the long-term impacts. At the same time, to provide the accessibility of population to work places, education facilities, shops, services, friends and family, it is necessary to take measures, which reduce ecological and social consequences as well as prevent traffic jams and accidents. For example, it is important to analyse if jobs created out of megapolis help to reduce commuting or not (Mäe *et al.* 2013). In general, the significance of transport is highlighted by the extent to which it encourages saving the most important resources of society and nature. It is referred to saving time and energy of people, improving the environmental conditions, reducing an amount of accidents, noise, vibration, etc. When designing the transport system, the main attention must be paid on:

- »» creation of transport frame;
- »» development of public transport systems;
- »» monitoring and evaluation of the main system parameters;
- »» implementation of innovative technologies in the transport field).

In the research of Schippl *et al.* (2016) the roadmap, which deals with the question who needs to do what by when in order to reach sustainability of urban transport, is discussed. This research is also exemplify three possible urban transformation pathways towards the urban target:

- »» the use of technological advances: the primary element of such an approach revolves around the idea of replacing conventionally-fuelled vehicles with battery electric vehicles and plug-in hybrid electric vehicles;
- »» shifting away from strong dependence on individual cars: this approach involves measures for compact urban development, promotion and integration of public transport, cycling, walking, car-sharing, and bike-sharing as well as measures to manage urban transport flows;
- »» overarching strategy to manage and to upgrade transport networks with a cohesive and long-term

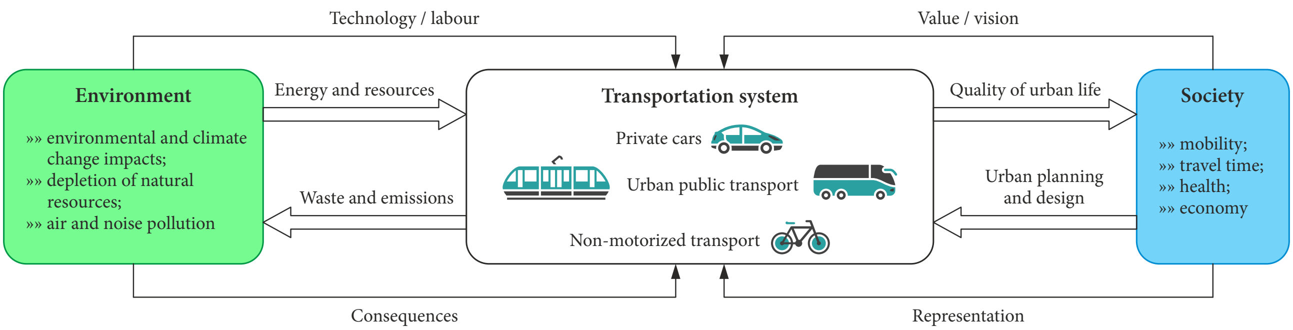

Figure 1. Interaction of transport system with environment and society

view: this strategy consists of plans to use incremental changes, mainly to improve the efficiency of public transport, to improve the infrastructure for walking and cycling and to promote alternatively-fuelled private cars, as well as includes learning from and share experiences with other cities.

One of the sustainable modes of transport is a light rail. Thus, the Ferbrache and Knowles (2016) released a special section on light rail and urban sustainability in the *Journal of Transport Geography*. The collection of papers provides insight to the role of light rail in broader sustainability-related initiatives, the benefits this might bring, as well as some of the disadvantages together with aspects how they are managed and may be improved. Overall, these measures are embedded within discourses, which promote improvements, growth, development and enhancement of urban quality and performance towards fostering sustainable cities. Metropolitan areas today urgently need a more sustainable, low-carbon transport systems. Steurer and Bonilla (2016) have elicited ways to build sustainable, low-carbon transport futures for such a system. Using stakeholder narratives as a basis, this paper has identified the main driving forces shaping sustainable transport futures, has developed four possible transport scenarios for the Mexico City metropolitan area as an example and has assessed whether stakeholders frame driving forces in a certain way. This scenarios method does not specify the future, which is preferred over others, but it helps to define such a way, which helps to make a balance between interests of different stakeholders.

1.2. Assessment of transport system sustainability

Monitoring and effective control in place are the keys to sustainability, which give an opportunity to make changes quickly in order to keep output at a certain level. Data is the most decisive element here, which allows for governments and companies to see, whether their outputs have a negative or positive effect on the whole city (as a whole). Opportunity to check and to control levels of pollutants can help to zone and to place them in areas of the city, where they could do the least harm, as well as can support approaches and measures to reduce their harmful output. This monitoring also creates a possibility to see, which technologies work better and more efficient to reduce pollution and what new innovative solutions could be used in particular areas to prevent further environmental problems and damages.

While the idea of "doing more with less" is conceptually very simple, to quantify and to assess the resource efficiency is more complex task in practice. Resources differ hugely: some of them are non-renewable, some – renewable; some are depletable, others are not; one part of them is hugely abundant, another part – extremely scarce. Stapleton *et al.* (2016) tried to quantify direct rebound effects, which result from increased consumption of cheaper energy service. The overall environmental impact also depends on: the indirect rebound effects, which occur from re-spending the savings in fuel costs on other goods and services (Chitnis *et al.* 2014); the economy-wide effects, which result from changes in prices and incomes (Lecca *et al.* 2014); and the transformational effects, which may result from induced changes in land-use patterns and transport systems. These broader effects are harder to quantify, less well-understood and usually neglected, but recent research suggests that they could be significant (Sorrell 2007).

The concept of "transport system sustainability" starts to be more useful, if it includes safety, reliability, economical efficiency and social significance. In the modern sense, the outcome of transport system development in the cities and regions divides into direct economic effect (only in the sphere of transport) and indirect economic, social and ecological effect, which takes into account its influence on economy, human and environment (outside the sphere of transport). It is to be noted that positive outcome of transport system development is created due to reduction of total social-economic damage in all parts of national economy.

Ecological effect involves the reduction of negative environmental impact of transport and connects with the decrease of air pollutant emissions and noise as well as with saving the urban area. Ecological outcomes are calculated according to the difference between volumes of air pollutant emissions or according to the difference between environmental conditions before and after the realization of certain project. Walking and cycling is widely assumed to substitute for at least some motorized travel and, thereby, to reduce energy use and CO_2 emissions. While the evidence suggests that a supportive built environment may be needed to promote walking and cycling, it is unclear, whether and how interventions in the built environment, which attract walkers and cyclists, may reduce transport CO_2 emissions. Brand *et al.* (2014) have aimed to evaluate the effects from introduction of new infrastructure for walking and cycling on CO_2 emissions, which come from motorized travel. Results of this research show that, while the current findings cannot exclude the possibility to get small effects of the new routes on CO_2 emissions, a more comprehensive approach to promote a higher "dosage" of active travel may be needed to achieve the substantial CO_2 reduction, which is necessary to meet climate change mitigation and energy security goals. Such promotion must be linked with policies targeted at mode shift away from private motorized transport (for example, urban car restraint and parking pricing, car sharing / pooling for travel to work, integrating bike sharing into public transport system, etc.).

Social effects are reached due to extension and improvement of transport system resources and on basis of measures, which do not require capital investments. These effects include growth of transport mobility, enhancement of road safety, improvement of human physical development, reduction of morbidity, increase of human lifetime and active labour activity, increase of leisure time and quality improvement of its usage, growth of population cultural and educational level. According to the *Global Status Report on Road Safety 2015* (WHO 2015), moving towards more sustainable modes of transport (such as non-motorized and public transport) has positive effects. They include not only the reduction of emissions, but also the growth of physical activity and, therefore, strengthening the population health. Goodman *et al.* (2014) have evaluated the effects of providing new high-quality, traffic-free routes for walking and cycling on overall levels of walking, cycling, and physical activity. First of all, these new local routes may have displaced walking or cycling trips in the short term. However, in the longer term they could generate new trips, particularly among those unable to access more distant destinations by car. These findings support the potential for walking and cycling infrastructure to promote physical activity.

To assess social effects of transport system improvement, one of the main criteria could be an accessibility. This is due to the fact that the accessibility is a fundamental concept to analyses transport systems. It can be defined as a measure of individual freedom to take part in activities existing in an environment. The research of Duran-Fernandez and Santos (2014) introduces an empirical metric for accessibility in Mexico, based on a classic potential model. This variable depends on the spatial distribution of socio-economic activities, on the land-use system and on the provision of transport infrastructure. The paper of Nordbakke and Schwanen (2015) has shown that the level of unfulfilled needs is shaped by both objective and subjective indicators of individual-level resources and abilities for mobility as well as contextual conditions for mobility. Actual participation in activities, which is shaped by transport-related factors in important ways, helps also to explain variations in the level of unmet needs. It is stated that unfulfilled activity needs are not merely a function of age, gender, education, health, car availability, driving license ownership and residential location. These factors help to explain the level of unmet activity needs as well, but general outlook on life, which is closely linked with personality traits, and actual level of activity are also important predictors.

In general, it is quite difficult to assess the sustainability level of transport system. However, Holden *et al.* (2014) suggest an assessment method to determine, whether countries currently meet the threshold values of four equally important primary dimensions of the sustainability level: safeguarding long-term ecological sustainability, satisfying basic needs, and promoting intragenerational and intergenerational equity. Indicators and threshold values for each of these dimensions are also defined in this research.

In addition to the profits from reduced congestion, multi-modal transport optimization brings benefits for cities through more efficient energy usage and improved customer experience (as it was noted earlier, the better the experience is – the more willing people are to use public transportation). In some scenarios, the system optimization can reduce costs through shared infrastructure – especially due to ICT resources – and by getting more out of existing infrastructure. In addition, it is possible to defer or to delay the need for new roadways or additional buses by optimizing the use of what the city has in place already.

Non-transport economic effects are generated outside the transport field and are expressed in economical assessment of infrastructural, social and ecological results, which come out of measures to improve the transport system.

1.3. Methods to evaluate the mobility system: "radar map" of indicators

There is an *Integrated Sustainable Mobility in Cities – a Practical Guide* (WBCSD 2016) to analyse urban mobility performance created under the auspices of the WBCSD. This process includes a data-driven assessment, using a comprehensive set of indicators to evaluate the mobility system.

As indicators are interrelated, the analysis helps also to clarify the interactions. For example, reducing congestion will improve situations with GHG, air pollution and travel time, but may increase traffic noise in some cases due to faster vehicle speeds. That is why SMP has developed methodologies to calculate the indicators from defined data inputs. The results are on a scale of 0…10, where 10 represents the best practice from a sustainability point of view. A "spider chart" or "radar map" presents the sustainability performance of each component and provides a holistic view. It presents each indicator in a single view, highlighting strengths and weaknesses of the city's mobility system. SMP has developed a set of 19 indicators, however, each city can develop its own indicators depending on the goals it has. This indicator set is intended primarily to provide an internal assessment and for the city to evaluate its progress over time or to compare with the target values. The challenge of this method is to find the right sources, to be alert to differences between various sources and to ensure that the same data is used in all relevant calculations. For example, the total vehicle mileage should be the same for all the indicators, to which it applies.

2. Results and discussions

2.1. Ways to improve efficiency

The EC has recently submitted a proposal to develop significantly the infrastructure for alternative fuels, which can be considered as a way of addressing the problem of low uptake of vehicles and lack of infrastructure (EEA 2015). As well as delivering clear environmental benefits (reducing average CO_2 emissions and air pollutant emissions etc.), the uptake of new technologies will also reduce dependency on oil. However, changes in the transport sector – such as renewing a vehicle fleet in the entire country – require time to get effect. Moreover, alternative fuel vehicles will not on their own solve other existing problems such as congestion levels, accidents and road safety, or noise levels. For this reason, additional fundamental changes in the direction of passengers and goods transportation are needed. These additional changes include avoiding the use of transportation where possible; shifting necessary transport from environmentally harmful modes to more environmentally friendly modes; and improving the efficiency of all modes of transport. In the longer-term, a coordinated complex approach is needed. This approach should integrate all of the previous policy measures: alternative-fuel vehicles, transport avoidance, shifting to less environmentally damaging modes of transport, new infrastructure, and financial measures. In order to gain public support, this coordinated approach must aim to address not just the environmental impacts of the transport system, but also it must create conditions for better health and improved quality of life.

2.2. Smart solutions for sustainable transportation systems

ICTs are able to provide more environmentally friendly and more economically viable solutions to some of the aforementioned problems faced in cities. As of today, ICTs' role in tackling environmental issues has not been completely identified. Potential areas, where ICTs can assist, include management of water sources, energy efficiency, and solid waste management, public transport infrastructure, reducing traffic congestion, growth of ICT infrastructure and managing its environmental impact with reference to problems related to EMF, visual aspects and air quality monitoring (OECD 2012). Replacing the actual urban infrastructures is often unrealistic in terms of cost and time. However, with recent advances in technology, it is possible to infuse the existing infrastructures with new intelligence. This includes digitizing and connecting the systems, so they can sense, analyse and integrate data, as well as respond intelligently to the needs of their jurisdictions. In short, there is an opportunity to revitalize them so they can become smarter and more efficient. In this process, cities can grow and sustain the quality of life for their inhabitants (IBM 2009).

There are a lot of ways, how cities can fix traffic congestion by deploying ICT. Advanced analytics and instrumentation can provide cities with the information, which they need to minimize congestion. Traffic lights can be synchronized and adjusted for optimal traffic flow. In-vehicle collision-avoidance systems can take actions to prevent congestion-causing accidents. Incident detention and notification systems can analyse information from cameras and vehicles to detect traffic problems, to alert drivers and to suggest alternative routes. One of the causes of the congestion and air pollution is the process, when people looking for parking spots. Up to 30% of traffic in cities these days can be produced by people searching for on-street parking, which makes this process a leading cause of congestion, pollution, noise, and fuel waste. Data analytics, combined with intelligent parking management systems, can help drastically reduce the number of cars looking for parking and direct them to empty spots more quickly. The data helps also officials to create parking meter pricing right – by monitoring the usage of parking and by optimizing prices for ideal occupancy rates. New technology, which combines cameras and geo-tracking with analytics, can "see", whether a particular spot is occupied or not, and transmit that information to a device within the car, such as, the GPS or driver's mobile phone, which could guide the driver to the closest available space. The knowledge helps also commuters to plan their trips better, so the data insights have a cascading impact. A recent study showed that travellers value reliable travel times even more than shorter travel times. Moreover, there are a number of factors, which make people feel that public transport is unreliable (Xerox 2017):

- »» buses showing up late;
- »» subways, which are too crowded;
- »» unreliable transfers between stops.

Communication plays an extremely important role in such conditions: when services are delayed, passengers want to know what and why is happening. Real-time data on electronic message signs and traveller apps helps to interpret issues, which cause delays – and ultimately to improve passenger satisfaction by keeping riders informed and by advising them on alternative travel options. At the same time, agencies can tap into social media data to improve services: sentiment analyses from Twitter feeds, for example, to show how riders perceive service – and to give officials the opportunity to get in touch with customers directly and they might even learn about blockages or failures on social media first. With the help of analytics and ICT, travel information systems and real-time route planning can plot multi-modal routes for travellers. Smart city transportation networks direct people, when and where they could switch from bus to subway, for example, to arrive at destinations at the lowest cost or fastest time. In addition, traffic and weather alerts can be delivered via smartphone applications to alleviate commute times.

In an era of big and small data as well as smart cities, significant repositories of data are becoming available for planners, decision-makers, and communities. The opportunity exists to utilize this data for support of evidence-based decision-making and collectively plan of the future for the cities. Citizens are generating large volume of data in the social media, voicing their opinions and sharing images of their neighbourhoods. Cities have many datasets, e.g., on public space, infrastructure and processes. Data scientists research how end-users can gain new, valuable insights to improve city processes and neighbourhoods. Data science researchers explore the boundaries of data gathering, storage, analytics and applications for cities – with an emphasis on generating valuable insights for both professionals, who work with the city-related projects, and citizens (ADS 2017).

Additionally, analytics can get more out of expensive transportation assets. Sensors and monitors can report on the actual condition of infrastructure so that operators can make better decisions, servicing equipment based on actual situation and not on a guess. This kind of asset management can squeeze many extra years when using the investment, and all this happens without compromising the equipment or passenger safety. With smart sensors, smart payment systems, GPS and all the other intelligent devices, which are gathering data as a part of a smart transportation system, the city and its residents are all better off when there is a plan for managing it (Smart Cities Council® 2015). Thus, traffic management creates a more efficient road network and reduces travel time and vehicle emissions. Smart public transit, in its turn, is easier and more convenient, attracting more riders and reducing reliance on automobiles.

2.3. Optimization of public transport system parameters: the case study of city of Naberezhnye Chelny

Road transport is the main source of environmental pollution in city of Naberezhnye Chelny (Russia), because its main stationary sources are situated outside or on the city borders. From the perspective of the city spatial planning, the situation with natural landscape plays a significant role: the city is located near water areas of Nizhnekamsk reservoir and Chelninsky bay as well as surrounded by forests. Open linear structure with the "classic" functional zoning was laid as a basis of urban planning organization with a parallel location of industrial and residential areas as well as suburban recreation zones. Longitudinal highways, which connect the residential areas, compose a transport-planning frame of the city. This fact gives an opportunity to attribute the planning scheme of its road network to rectangular. The main "diameter" of the city is a longitudinal arterial road, which includes M. Jalil avenue, Naberezhnochelninsky avenue, and Mira avenue.

Taking into account that the main part of peak-hour trips concerns communications "home–work" and "work–home", the division of industrial and residential areas in the city creates problems on intersections of longitudinal and transversal arterial roads. It is because there were special bus routes to deliver employees to industrial zones, which disappeared. On the other hand, the route network of public transport was not adapted to new situation. These facts caused that people had started to use an individual transport. The special survey was organized to find out transport districts, which were not covered by the existing route network sufficiently, as well as to understand conditions, under which public transport and non-motorized modes of transport could be more attractive for inhabitants. To improve the urban public transport system, a macroscopic transport model of the city was built. To create such kind of model, it is necessary to have the following input data:

- city map with road network and points, which generate and attract the traffic flows;
- parameters of existing public transport routes and stops in the city;
- quantitative and qualitative structure of the vehicle fleet, which serves each route;
- technical and economic characteristics of each vehicle type (capacity, travel speed, etc.);
- average speed of traffic flow on the road network segments;
- number of lanes and network capacity for each road network segment;
- traffic density on the road network segments;
- maximum permissible time interval between public transport vehicles;
- irregularity factor of walking time for passengers to reach a PTS;
- total population, share of working people, numbers of students, of workplaces, of people employed in the service sector.

By developing a new route network of bus transport, it is necessary to take into account the following aspects:

- all transport districts in the city must be connected between each other by direct routes without any transfer; Special attention must be given to new districts with underdeveloped transport infrastructure as well as to districts, which according to survey were pointed out by respondents as districts with low service of public transport;
- improvement of route network must lead to the reduction of situations, when routes overlap each other;
- despite the general decrease of routes number, the time interval between arriving buses must correspond to standard values and satisfy fully transport demand of population;
- choice of vehicles for each route and bus timetable must be done according to predicted values of transport mobility and must be corrected according to changes of traffic parameters.

Although the existing configuration of road and street network do not allow to avoid fully the overlapping of public transport routes, it is possible to reduce significantly an amount of routes, which pass through the same segment of road network, thus having saved an opportunity to satisfy mobility of urban population. The Figure 2 presents a part of existing route network together with showing route numbering, which pass through problematic segment of road network. The upgraded bus route network is shown on the Figure 3. The comparison of transport load values on the most problematic segments of road and street network according to existing and proposed route networks are presented on the Figure 4: numbers marked with *red* colour specify an amount of private cars passing through this segment, numbers marked with *blue* colour – volume of public transport passengers.

Taking into account the demand on passenger transportation for each segment of transport network, an optimal amount of vehicles (depending on their types) for each route was calculated. As a result of tests on the transport model of the city of Naberezhnye Chelny, the following outcome was generated: the amount of routes could be reduced from 27 to 15. Additionally, an opportunity was created to adapt a time interval between buses according to growing transport demand. Amount of vehicles on routes could be reduced by increasing the share of

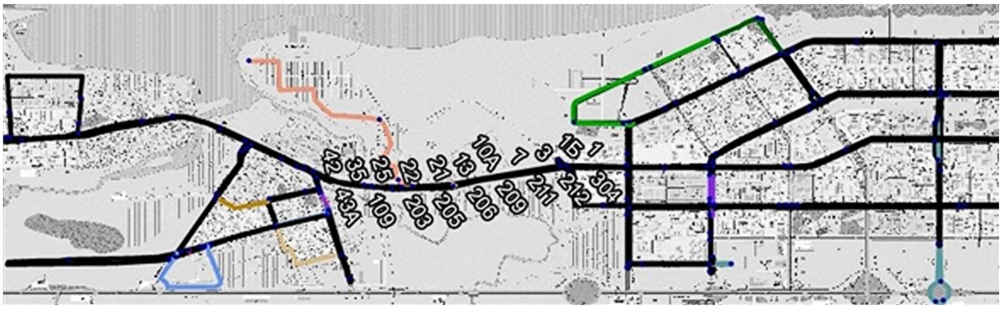

Figure 2. Scheme of the existing route network

Figure 3. Scheme of the proposed route network

a) b)

Figure 4. Distribution of transport load according to: a – existing passenger flow and route network; b – predicted passenger flow and upgraded route network

buses with large capacity, which run on gas engine fuels, for example, NEFAZ-5299 with capacity of 115 passengers (RariTEK 2021). According to the proposed traffic scheme, a number of large buses must be 119 (instead of actual 19) as well as a number of small buses – 127 (instead of actual 400 buses of small and middle capacities). Despite the decrease of bus amount on routes, their frequency of movement during peak-hours increases (time interval in peak-hours is 3…4 min). During the period out of peak-hours, the frequency corresponds to interval of 6 min.

2.4. Efficiency assessment of the proposed solution

The efficiency of the proposed solution consists of 4 components:

- »» positive social effect;
- »» economic efficiency;
- »» increasing environmental friendliness;
- »» sustainability of the urban transport system.

For example, the economic efficiency could be considered as savings on costs per one transported passenger associated with fuel products. Such effect could be reached by reducing the amount of vehicles and the total amount of km on routes as well due to operation of buses, which run on gas engine fuels. To calculate the economic efficiency *EE*, the following equation is used:

$$EE = \sum_{k=1}^{3} \frac{L_k \cdot FC_k \cdot P_k}{100 \cdot N_k \cdot q_k}, \quad (1)$$

where: *EE* – economic efficiency [RUB/person]; *k* – type of buses, which operate on route ($k = 1$, if buses have a small capacity (18 persons) and run on a diesel engine fuel; $k = 2$, if buses have a large capacity (115 persons) and run on diesel engine fuel; $k = 3$, if buses have a large capacity (115 persons) and run on gas engine fuel); L_k – total amount of km done by all buses related to type k [km]; FC_k – fuel consumption of buses related to type k [L/100 km]; P_k – price of fuel used by buses related to type k [RUB]; N_k – amount of buses related to type k; q_k – passenger capacity of bus related to type k [persons].

According to the existing scheme of traffic organization, the economic efficiency $EE_{existing}$ corresponds to the following value:

$$EE_{existing} = \frac{14875.5 \cdot 10 \cdot 36}{100 \cdot 400 \cdot 18} + \frac{690.1 \cdot 55 \cdot 11}{100 \cdot 19 \cdot 115} \approx 9.35 \text{ RUB/person}.$$

According to the proposed scheme of traffic organization as well as when replacing the part of diesel-powered buses, which have small passenger capacity, with vehicles, which have large capacity, the value of the same parameter $EE_{proposed}$ is following:

$$EE_{proposed} = \frac{2780.8 \cdot 10 \cdot 36}{100 \cdot 127 \cdot 18} + \frac{2879.7 \cdot 26.5 \cdot 36}{100 \cdot 119 \cdot 115} \approx 6.39 \text{ RUB/person}.$$

According to the proposed scheme of traffic organization as well as when replacing the part of diesel-powered buses, which have small passenger capacity, with vehicles, which have large capacity and are powered by gas engine fuel, the value of the economic efficiency $EE_{proposed}$ is following:

$$EE_{proposed} = \frac{2780.8 \cdot 10 \cdot 36}{100 \cdot 127 \cdot 18} + \frac{2879.7 \cdot 55 \cdot 11}{100 \cdot 119 \cdot 115} \approx 5.65 \text{ RUB/person}.$$

The positive social effect could be assessed by using an amount of transported passengers as well as by using the different types of time delays and, especially, their reduction. Time delays concern not only time spent by passenger waiting for a bus and idle time spent by bus on bus stops, but also idle time spent in traffic jams. To combine particular values of passenger travel time between two transport districts into a single criteria of social effect SE, it is necessary to adjust them to a common basis (per one transported person):

$$SE = \frac{\sum_{l=1,\, m=1}^{p} t_{l \times m}}{\sum_{k=1}^{3} N_k \cdot q_k}, \qquad (2)$$

where: SE – social effect [min/person]; l – index number of origin district; m – index number of destination district; $t_{l \times m}$ – passengers' travel time from district l to district m [min]; p – number of transport districts.

Calculation of passenger travel time between each pair of transport districts is carried out with the help of model for both existing and proposed traffic schemes. Taking into account the existing plan of traffic management, the value of social effect $SE_{existing}$ is following:

$$SE_{existing} = \frac{138544}{400 \cdot 18 + 19 \cdot 115} = 14.76 \text{ min/person}.$$

Considering the proposed plan, the result of $SE_{proposed}$ is:

$$SE_{proposed} = \frac{138544}{127 \cdot 18 + 119 \cdot 115} = 8.41 \text{ min/person}.$$

The reduction of passenger travel time arises, especially, due to elimination of delays, which were spent by buses on bus stops to pick-up/drop-off passengers. This was achieved through the avoidance of route overlapping as well as partial substitution of buses with small capacity for buses with large one. According to the existing scheme of traffic management, ca. 20 different routes can go through the same bus stop. It means that 5…10 buses could arrive on the same bus stop in the same time. The proposed plan of traffic management reduces a number of routes going through each PTS and, thus, gives an opportunity to use the idea that 1 bus with capacity of 115 passengers could substitute for 6 vehicles with capacity of 18 passengers.

To quantify the impacts from such changes, maximum idle time to drop-off 115 passengers and then to pick-up the same number of persons was calculated for each type of buses, which pass through a stop. Such parameter is following:

»» for bus with capacity of 115 passengers:

$$t_{PTS} = \frac{(115 + 115) \cdot 1.2}{3} = 120 \text{ s} = 2 \text{ min};$$

»» for bus with capacity of 18 passengers:

$$t_{PTS} = 6 \cdot \frac{(18 + 18) \cdot 1.2}{1} + \frac{(7 + 7) \cdot 1.2}{1} = 276 \text{ s} = 4.6 \text{ min}.$$

To compare minimum idle time for each bus type on a stop, the calculation of time to drop-off and then to pick-up one passenger was done:

»» for bus with capacity of 115 passengers:

$$t_{PTS} = \frac{(1 + 1) \cdot 1.2}{3} = 0.8 \text{ s} = 0.013 \text{ min};$$

»» for bus with capacity of 18 passengers:

$$t_{PTS} = \frac{(1 + 1) \cdot 1.2}{1} = 2.4 \text{ s} = 0.04 \text{ min}.$$

Thus, by using buses with large capacity and by the same amount of passengers, it is possible to reduce pick-up and drop-off time by half in comparison with small class buses.

Environmental performance is provided by 2 ways. The first tool assumes to reduce the total amount of buses, which go through problematic sections of the road network. The second approach is based on the idea to substitute diesel-powered buses by more ecological ones, which runs on gas engine fuel (methane). The volume of pollutants VP is calculated according to the following equation:

$$VP = \sum_{k=1}^{3} \frac{N_k \cdot H_k}{1000}, \quad (3)$$

where: VP – volume of pollutants [g/1000 L]; H_k – content of pollutants in the engine exhaust gases [g] (RariTEK 2021).

The Table 1 presents values of pollutants taking into account the following scenarios: existing traffic scheme and proposed traffic schemes with buses of large capacity, which run on diesel or natural gas engine fuels.

Positive influence of the proposed solution on the transport system sustainability could be assessed with regard to the approximation of its parameters to target values of the system, which are recommended in the different regulatory documents. For this purpose, an integrated efficiency indicator was developed and "radar map" was built. The key efficiency parameters were pointed out and calculated for existing and proposed route networks. To use the method of "radar map", the indicators have to be aggregated in an overall index on a scale from 0 to 1, where 1 represents the best practice from a sustainability point of view. Reference values (left side) and normalized values (right side) of parameters for each scheme are presented on the Table 2. Then these parameters were compared with target values (Figure 5). The larger size of the radar area is, the closer route network parameters are to the target values. Sizes of radar areas are equal to 0.872, 1.147 and 1.162, respectively. Taking into account that integrated indicator of developed route network is practically equal to radar area of standard values and 32% bigger in comparison with existing scheme, it could be concluded that proposed management solution is efficient.

In addition, risk analysis in relation to the management of urban bus transport was done from the perspective of Transport Department in the city of Naberezhnye Chelny. This analysis covers the determination of risk areas indicating points of system vulnerability, risk levels as well as proposition of management tool to affect the situation. It was established that to mitigate the most dangerous negative risks it is necessary to introduce a comprehensive set of measures. This set of measures is connected first of all with smart working conditions for drivers as well as with increase of population loyalty to public transport, in general, and to buses with large capacity, in particular.

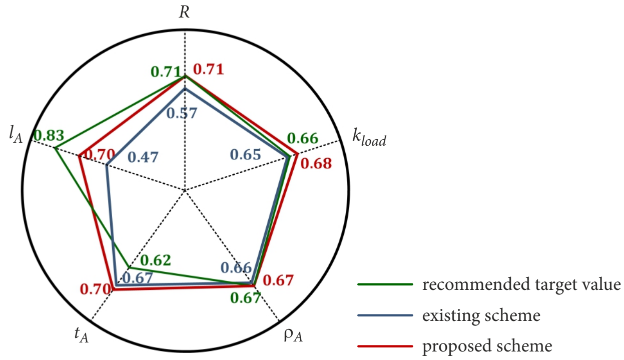

Figure 5. "Radar map" of the route network's efficiency

Dependence of risk on investment and missed profit was determined and calculated according to the following equation:

$$R = 0.8111 - 0.0031 \cdot X - 5.0852 \cdot 10^{-5} \cdot Y + 8.5579 \cdot 10^{-6} \cdot X^2 + 4.927 \cdot 10^{-8} \cdot X \cdot Y + 3.9893 \cdot 10^{-9} \cdot Y^2, \quad (4)$$

where: R – investment risk [RUB]; X – amount of investments [RUB]; Y – amount missed profit [RUB].

The Figure 6 shows a risk surface for different scenarios of city economic development depending on the size of investment, which is realized to buy buses with large capacity running on gas engine fuel.

Table 1. Volume of pollutants

Name of pollutants	Volume of pollutants by different schemes of traffic management [kg/day]		
	Existing scheme	Proposed schemes with buses of large capacity	
		Buses run on diesel engine fuel	Buses run on gas engine fuel (methane)
CO	569.1	472.7	330.9
NO_x	1117.3	945.4	530.8
C_xH_y	3956.9	3437.8	1266.7
Soot	3646.3	3008.0	2260.7

Table 2. Comparison of the main route network's efficiency parameters

Parameters	Existing scheme		Proposed scheme		Recommended target value	
	raw value	normalized value	raw value	normalized value	raw value	normalized value
Average length of routes l_a [km]	36.80	0.47	20.6	0.70	12.00	0.83
Indicator of the risk probability, which influences on delivery time R	3.00	0.57	2.00	0.71	2.00	0.71
Coefficient of maximum highway load k_{load}	1.02	0.65	0.93	0.68	<1.00	0.66
Average coefficient of unstraightness ρ_a	1.48	0.66	1.45	0.67	1.42	0.67
Average passengers' travel time between transport districts t_a [h]	0.53	0.67	0.48	0.70	<0.62	0.62

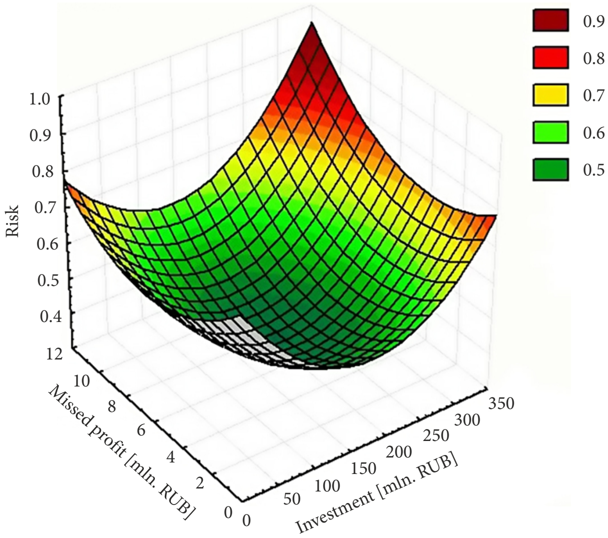

Figure 6. Risk surface

Conclusions

Today there is much talk about what does the concept of sustainable city mean. Technology and infrastructure are the key points in ensuring sustainability, but they cannot be really effective without coordinated planning, vision and managerial decisions. Transportation system is the basis of any city: it contributes to economic system development through transportation of passengers to their places of work and cargos' delivery to all enterprises of the city. At the same time transport system is the main source of environmental pollution. Thus, the advantages of increased mobility need to be weighed against the environmental, social and economic costs that transportation systems pose.

The possibility to increase the sustainability of the transport system was considered on the example of the city of Naberezhnye Chelny (Russia). The following tools were chosen: optimization of bus route network as well as optimization of vehicle fleet on routes in accordance with the real transport demand of population. It was shown that decrease of route overlapping, public hearing of local inhabitants by design of new routes, usage of buses with large capacity as well as use of more environmental friendly types of buses allow to increase the quality of transport service and the population mobility together with decrease of negative environmental impact as well as load on the urban road network. In addition, complex parameters to assess the efficiency of proposed solution and the sustainability of transport system were described.

Author contributions

Irina Makarova is the author of the idea and conception of this paper, also she supervised the whole project and critically reviewed and corrected the study proposal.

Ksenia Shubenkova created the model and wrote the draft of the manuscript.

Anton Pashkevich translated into English and corrected some statements.

Disclosure statement

We declare that we do not have any competing financial, professional, or personal interests from other parties.

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