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Research paper

Estimation of social costs resulting from mobility changes caused by COVID-19 pandemic

Andrzej Brzeziński[1], Tomasz Dybicz[2], Karolina Jesionkiewicz-Niedzińska[3], Piotr Olszewski[4], Beata Osińska[5], Piotr Szagała[6], Łukasz Szymański[7]

Abstract: The COVD-19 pandemic has changed the mobility patterns of city dwellers worldwide. These changes apply to the number of trips made, their durations and directions as well as transport modes chosen for travelling purposes. In general, although the number of trips decreased, the use of cars increased and that of public transport declined. These mobility changes were induced by the fear of travelling in crowded vehicles and the extent of restrictions introduced by the governments. The effects of such changes are hard to assess and their evaluation is a complex issue. Based on data available about the transportation system in Warsaw and analysis of Big Data (comprising SIM card movements, acquired from mobile phone network operators), a research project has been carried out under the "IDUB against COVID-19" programme. Transportation models had been built which enabled estimation of the number of trips made at each stage of the pandemic in the spring 2020 and identification of differences through comparison with the models developed for the pre-pandemic conditions (year 2019). The calculations enabled assessment of the social costs of the pandemic associated with the urban transportation system, brought about mostly by changes in using private and public transport modes. The cost efficiency of public transport decreased as a result of limits on the number of passengers per vehicle introduced by transport authorities.

Keywords: COVD-19 pandemic, trip modelling, mobility, social costs, public transport, Big Data

[1]Ph.D. Eng., Warsaw University of Technology, Faculty of Civil Engineering, al. Armii Ludowej 16, 00-637 Warsaw, Poland, e-mail: andrzej.brzezinski@pw.edu.pl, ORCID: 0000-0002-1256-6007
[2]Ph.D. Eng., Warsaw University of Technology, Faculty of Civil Engineering, al. Armii Ludowej 16, 00-637 Warsaw, Poland, e-mail: tomasz.dybicz@pw.edu.pl, ORCID: 0000-0001-6151-2737
[3]Msc. Eng., Warsaw University of Technology, Faculty of Civil Engineering, al. Armii Ludowej 16, 00-637 Warsaw, Poland, e-mail: karolina.niedzinska@pw.edu.pl, ORCID: 0000-0002-7222-114X
[4]Prof., DSc., PhD., Eng., Warsaw University of Technology, Faculty of Civil Engineering, al. Armii Ludowej 16, 00-637 Warsaw, Poland, e-mail: piotr.olszewski@pw.edu.pl, ORCID: 0000-0003-3470-4471
[5]Msc. Eng., Warsaw University of Technology, Faculty of Civil Engineering, al. Armii Ludowej 16, 00-637 Warsaw, Poland, e-mail: beata.osinska@pw.edu.pl, ORCID: 0000-0001-9079-4614
[6]Ph.D. Eng., Warsaw University of Technology, Faculty of Civil Engineering, al. Armii Ludowej 16, 00-637 Warsaw, Poland, e-mail: piotr.szagala@pw.edu.pl, ORCID: 0000-0002-9186-2700
[7]Msc. Eng., Transeko, ul. Śniadeckich 20/13, 00-656 Warsaw, Poland, e-mail: l.szymanski@transeko.pl, ORCID: 0009-0003-3494-2573

1. Introduction

When facing epidemiological threats, especially pandemic conditions, city dwellers change their mobility patterns (number of daily trips/person) significantly. These changes result both from their self-isolation in response to their own health and life concerns and from decisions taken by the authorities. Mobility has been largely affected by restrictions imposed, and especially by shutdown of educational institutions (preschool facilities, schools and universities), commercial premises and workplaces (offices, services, production plants). Some changes have also been brought about by the introduction of teleworking and online education. Mobility has also been reduced as a result of restrictions imposed on transportation, such as restrictions or bans on car driving, bicycle riding or limits on the numbers of passengers in public transport vehicles. The most comprehensive comparison can be found in [1], where so called Oxford Stringency Index was calculated being the mean of the confinement and public information campaign indices. It can be noticed that the for example measures applied in Poland were not as strict as in other countries. The study also found that there was no correlation between the change in the fatality numbers and the stringency of the measures. The limitation of the study is that it only compares nation-wide data, without reference to individual cities.

As the epidemiological threat increases and the further restrictions are imposed, mobility changes take place accordingly. Those changes build up until reaching a peak when the demand for commuting and travelling diminishes to a significant extent. When the pandemic wave retreats and the respective restrictions are relaxed, mobility starts increasing, although it may take some time for it to achieve the pre-pandemic levels. It may also adopt different forms – e.g. the share of private transportation trips increases. All of those factors impact the operations of the urban transportation system which, depending on people's mobility changes, starts being used in a different manner than before. The main reasons behind that change are the choices made with respect to transport modes.

The social effects of mobility changes induced by the pandemic are not easy to assess and their evaluation is ambiguous and complex. Some of the consequences may be positive and bring social benefits (e.g. less congestion, less air pollution and noise), while the other ones are negative (e.g. increased car use, more severe road accidents, increased costs of public transport per passenger).

The available data on urban transportation systems and analysis of Big Data (on movements of SIM cards of mobile phone users) allow for development of transportation models which make it possible to estimate the numbers of trips made by people at each stage of the pandemic (defined by the severity of restrictions imposed) and to identify differences by comparing them with pre-pandemic transportation models [2–5]. On those grounds it is possible to estimate social costs associated with the transportation system, resulting from mobility-restricting decisions as well as to analyse the health risk of using public transport. The models make it possible to predict the numbers of passengers in public transport and compare them with the number of places offered in vehicles. This method can be used for better management of public transport systems, that is planning the routes, frequency of services or capacity of vehicles. The problem is important, both from the point of view of health safety of passengers in public transportation, capability of the transport operators to prepare the supply of services offered and also from the point of view of the operating costs of the entire urban transport system. Currently, the transport providers do not have this kind of tool at their disposal.

The article presents the results of the research project entitled "Method of assessing the social impact of changes in personal mobility in an epidemic state together with tools to support transport management", carried out at the Warsaw University of Technology under the "IDUB against COVID-19" programme. Using Warsaw Metropolitan Area (WMA) as a case study, the results demonstrate how to use transportation models developed using SIM card data to assess the impact of the pandemic and associated restrictions on personal mobility, operation of the transportation system and the impact of the transportation system on its surroundings. The project considered three stages of the pandemic which occurred in the spring of 2020 (March, April and late May/early June). The restrictions applicable in Poland at each of these stages are presented in Table 1. The mobility results for 2020 were compared to the comparable pre-pandemic period in 2019.

Table 1. The most important restrictions and mobility limitations imposed in Poland during the three phases of the pandemic

Year 2020 – phase 1 **17–31 March**	**Year 2020 – phase 2** **8–29 April**	**Year 2020 – phase 3** **19 May – 11 June**
– Cancelled open-air mass events ≥ 1000 people ≥ 500 people in confined spaces – Closed schools and universities – Suspended activity of cultural institutions – Social gatherings limited to no more than 2 people – Trips limited as much as possible (except for home and work commute) – Going outside only if absolutely necessary – e.g. shopping, buying medicine, medical appointments, dog walking	– The same as in phase 1 plus: – Children younger than 18 years forbidden to leave home unsupervised – Parks, embankments and beaches closed – Services closed (e.g. hairdressers, beauticians) – Restricted hotel activities (for work travel only) – Religious gatherings limited to 5 people – Access restrictions and partial closing of the Polish borders (14-day quarantine) – Limited number of shoppers in stores	– Loosening up of restrictions: – Opened shopping malls, libraries, museums, art galleries, physiotherapy centres – Opened preschool institutions – Hairdressing and beauty parlours, restaurants and cafes resume activity – Access limits in stores and food courts are cancelled – Cultural institutions resume activity – Districts are classified as red, yellow or green (with adequate restriction levels)

2. Mobility changes under COVID-19 pandemic conditions

As a result of huge changes in the lifestyle of societies brought about by the COVID-19 pandemic, the extent of transportation behaviour changes and associated social costs have been analysed in several countries. The analyses were based on information from several sources:

data coming from various detection systems as well as movements of the SIM cards [6–8] which allowed the researchers to determine the numbers of trips made during the pandemic and the extent of their decrease compared to the pre-restriction phase. Detailed interviews performed in Germany [9,10]) or Poland [11] provided a broader picture of transport behaviour in households. A special emphasis was put on the use of public transport [8,12].

The lockdown which resulted in closed schools, universities, most of services as well as transition to teleworking from home of large parts of the society has brought a significant decrease in the general number of trips in all cities and countries analysed. The number of trips has dropped as much as 75% in Rome and Santander in Spain [6]. In Sweden, where practically no lockdown has been introduced, and in Germany the number of trips went down by about 40% [8,13]. In Switzerland, the trip number decreased by about 60%. The number of kilometres travelled each day dropped on average by 60% for those who travel or commute by car and by 95% for train passengers. For larger households, a bigger daily decrease in the distances travelled was recorded (up to 60% in the first restriction phase). In case of smaller households (comprising mostly a single person) the decrease amounted to 50% [10].

The purpose of the interviews performed in Poland was to assess the total reduction of the time spent on daily travelling in two separate 7-day periods, just before the introduction of restrictions and just after their implementation. A significant reduction of the time spent on travelling was recorded during the pandemic regardless of the age of the respondents. The extent of the reduction depended on factors such as: the purpose of travel, transport mode, household size, respondent's fear of the coronavirus, and occupation. The longer the trips were before the pandemic, the bigger the reduction of their duration during the pandemic. With each additional household member, the travel duration dropped by 2.46%. Another reason behind the phenomenon was the fear of the coronavirus. The travel duration decreased to a slightly larger extent among women, which was probably caused by the need to take care of children once the preschool care institutions stopped working. The traveling time went down dramatically in case of pupils (by 80.21% on average) who studied online when their schools had been closed. For university students, the reduction was a bit less significant (70.78%). The lowest decrease was recorded for full-time lower-level employees. In the latter case, the commuting time dropped only by 53.39% [11].

It was the public transport that suffered the most under the restrictions. In many cities like Budapest, Lyon, Nice, Toronto, San Francisco, Washington DC and countries like the Netherlands, the number of public transport users dropped during the lockdown by almost 90% [7,14–18]. In Germany, the share of public transport in general trip making went down from 23% to 13% among representatives of all age groups, and among young people – from 47% to 19%. In Sweden, the reduction of the share of public transportation depended on the region and varied between 40% (Västra Götaland) and 60% (Stockholm and Skåne). The number of metro and train passengers dropped by about 60%. A less significant decrease was observed for trams (40–50%), and the smallest one – for buses (30%) [8]. As the number of passengers went down, the revenue from tickets dropped as well, while the operating costs went up. Such a tendency could be observed e.g., in the Spanish city of Santander, where at the moment of loosening the restrictions, the operating costs, which had dropped by 50% during lockdown, increased due to the need to provide a sufficient number of buses for a much lower acceptable number of passengers on board, introduced due to the necessity of keeping an adequate social distance [6]. Public transportation analyses performed in Sweden were based first and foremost on the data derived from the information on tickets sold. The latter demonstrated that at the beginning, passengers stopped buying long-term tickets and started purchasing short-term ones, previously bought mostly by tourists, who were basically absent at the first stages of the pandemic. The sales figures for long-term tickets, annual passes and school tickets went up in mid-April, which demonstrated the tendency of passengers to get back to their public transport habits [8]. In most cases, however, public transport trips, unlike private transport, did not reach the levels comparable to the pre-pandemic period.

The number of private transportation trips dropped much less than that of public transport. The general number of trips made in passenger cars went down in the countries and cities analysed by about 40–50%. In the following months when restrictions were gradually being relaxed, the use of private transportation modes was returning very quickly to its pre-pandemic levels. For instance, in Rome at the beginning of the restrictions trips made by passenger cars were reduced by 40%, while in May 2020 – by as little as 26%.

As there was less traffic on the roads, cars could be driven faster, which resulted in reduced duration of the trips. At the stage of the strictest restrictions in Switzerland, the speed of passenger cars increased by about 15 km/h in the morning and afternoon rush hours. No major speed changes were observed, however, during mid-day. In the post-lockdown period, the speed went back to its 2019 levels for rush hours only. It was observed that during the mid-day speed dropped in relation to the previous year, mostly in the areas with speed limits of 20–50 km/h. Most likely it resulted from a bigger number of shopping trips generated at that time compared to the pre-pandemic period, accompanied by a reduction in the number of trips performed using public transportation [10]. In Santander, Spain, travel times of public buses under lockdown were 30 percent lower, which reduced the operating costs by almost 50% [6].

3. The use of Big Data

In the research project described above, trip models were built using data from a mobile phone network operator, comprising movements of the so-called active SIM cards[1]. These are the cards which are logged into the operator's system during the data collection period. When the cards are active their users can either:

- Travel between different traffic zones,
- Do not travel (their cards do not move),
- Travel within the area of a single traffic zone (which means that they most likely do not burden the transportation system).

Data on SIM card movements are presented as matrices of trips made between traffic origins and destinations, aggregated to traffic zones normally used for the purpose of building a trip model. They represent not only movements, but also trip-generation potential of the various zones and make it possible to perform analyses at any given period (depending on

[1] Data from SIM cards for 2020 were purchased under the project, those for 2019 were provided by the capital city of Warsaw.

expectations defined at the stage of data acquisition from the operator) e.g., for the specific hours of the day [19]. It must be noted that generally in case of data derived from SIM cards, it is impossible to determine what kind of transport modes are used by passengers. Hence, their application is justified mainly when trip generation and spatial distribution models are created, before the modal split stage.

Data on SIM card movements were collected for the entire Warsaw metropolitan area (WMA) which encompasses Warsaw and its surroundings. The movements wholly within the analysed area were considered to be internal trips. Movements beginnings or endings of which were located outside of the Warsaw metropolitan area were classified as external trips. These were often long distance trips, which started outside of the Warsaw metropolitan area and ended within its boundaries or vice versa. Data derived from SIM cards enable such a comprehensive approach and the inclusion of both local and long distance movements in the model under construction. Those data are presented as a matrix broken down into inner zones (within WMA's boundaries) and external ones (outside of it). The data collected from SIM cards identifying movement origin and destination points were assigned to traffic zones. In the project a total of 1310 zones were defined, including: 47 zones mapping the area outside of Poland, 29 zones mapping Polish voivodships (provinces) and their capital cities, 307 zones mapping the Mazovian voivodship, 143 zones representing communes and towns surrounding Warsaw in the Warsaw metropolitan area, and 784 zones in Warsaw itself. Using these zonal definitions, a total of 72 hourly trip matrices were developed – 18 independent matrices which mapped different kinds of trips for 2019 and three periods in 2020.

Data on people's movements acquired from a single mobile network operator were expanded to the entire population by applying the so-called "SIM card multiplier". The multiplier is determined by the mobile network operator for each movement (trip) made between a pair of zones, taking into account for each zone: population (residents older than 10 years), the operator's share in the SIM card market, number of people owning more than one mobile phone and the number of SIM card users who provided their marketing consent. In this case, the averaged value of SIM card multipliers applied was equal to 8.65.

The movement data were acquired for representative working days (Tuesday, Wednesday and Thursday). For the first phase of the pandemic, those days were selected from the period 17–31.03.2020, for the second phase – 8–19.04.2020 and for the third phase – 19.05–11.06.2020. Data for representative working days in 2019 were selected from the period between 02.04 and 18.06.2019. The analyses were performed for the period of one day (24h) and – for the purposes of building a transportation model – for the morning peak hour.

4. WMA transportation model at the time of COVID-19

Based on Big Data, transportation models were built which reflected trips performed in the Warsaw metropolitan area in the successive three phases of the pandemic in the spring 2020, each characterized by a different level of restrictions (Table 1). A model was also built for spring 2019, with that period established as a reference period enabling comparison of the results. Models were built in a conventional, four-step way, but the trip generation and spatial distribution steps were replaced with trip matrices calculated based on SIM card data. The modal split for each pandemic stage was determined on the basis of a questionnaire survey [20]. It was assumed that during a strong impact of the pandemic, standard modal split models (e.g. those described in [21] do not work due to the totally different criteria of selection of transport modes, resulting primarily from imposed restrictions of access to public transportation and health concerns of their passengers. Models were built for the morning peak hour (7:30–8:30) due to its importance for the operation of public transportation in Warsaw.

Transportation models for the morning peak hour were developed within the entire Warsaw metropolitan area for all the four periods (with 2019 as a reference period and 2020 in the three pandemic phases). Each of the models included trips inside of Warsaw, its surrounding area, between Warsaw and the WMA zones, as well as external trips (outside of WMA). Each of the partial matrices included in the total trip matrix was developed taking into consideration specific characteristics of trips included in each category. For instance, for a trip between transport zones in Warsaw, a strong emphasis was put on detection and elimination of noise, or, in other words, of a large number of "false" trips, generated between closely located traffic zones as a result of dense distribution of mobile network transmitters. Noise is generated due to technological characteristics of mobile telephony system. It occurs when a stationary phone switches between base stations situated in two neighbouring zones. Because of the technology limitations, a mobile network operator cannot eliminate that phenomenon. The only solution is to apply a detailed data analysis in order to detect such cases and remove them from the data set. Noise is characterized by the occurrence of very large numbers of "trips" between selected pairs of zones, especially between neighbouring zones. That issue does not apply, however, to all movements between every two neighbouring zones, which makes it impossible to correct the data automatically. It is estimated that overlooking this issue could result in an overestimation error of number of trips up to 10%.

Trips which most likely did not include any motor vehicles or were performed for recreation purposes were also identified and separated. They included, for example, trips to parks, forests, cemeteries, gardens etc. from zones located in their close vicinity. If the distance between the origin and destination zones was bigger, e.g. trips from or to Warsaw to or from zones located outside of WMA, it could be assumed that 100% of these trips were made using motor vehicles.

In order to represent more accurately trips made inside of Warsaw and the area around the capital city, the peak hour trip model was created using movements which started and ended within three morning rush hours: 6:00–7:00 am, 7:00–8:00 am and 8:00–9:00 am. For these hours, the distributions of trip starting and ending times (in 15-minute intervals) were established based on household travel surveys (trip diary) performed in Warsaw in 2015 [22]. This made it possible to identify trips which were actually present in the transportation system within the peak hour under examination, that is exactly between 7:30 am and 8:30 am.

Verification and correction procedures were applied before the use of each of the matrices of trips which started and ended during each of the hours considered. It was necessary to adjust the trip matrices for those movements between zones which in the operator's database were equal to less than 5 and, as a result, were not disclosed. Whenever there are fewer than five trips for a given pair of zones, the operator cannot disclose their exact number due to the personal data protection rules. This results from the Polish legislation which imposes on the operators the obligation to keep processed data anonymous. Nevertheless, the operator can provide a list of pairs of zones for which such cases have arisen as well as data on the total number of trips which started and ended in each zone. This makes it possible to develop a complementary model of distribution of trips other than those disclosed by the operator. For the peak hour matrices, an averaged share of undisclosed trips in the total number of trips varied between 5% and 7%.

The last stage in the model preparation procedure was separation of car and public transport trips. For that purpose, for the year 2019 previously developed modal split model was used, based on home interview surveys performed among Warsaw households in 2015 [22]. In the case of 2020 model, data from transportation survey performed by the Warsaw town hall was used, which identified changes in travel behaviour before and during the pandemic, including modal preferences [20]. These analyses revealed, among others, that before the COVID-19 pandemic, 56% of the interviewed Warsaw residents used bus, tram or metro, while 49% used their cars. When the pandemic-related restrictions reached their peak, the use of the public transport decreased to 28%, mostly as a result of increased use of passenger cars (61% as drivers and 9% as passengers).

As the first step, the transport model for the Warsaw metropolitan area for 2019 was developed. This model was compared to the previous transport model, developed based on conventional household travel survey [23]. Table 2 shows satisfactory compliance of both models. Figures 1 and 2 show good agreement between observed and modelled traffic and passenger flows which were used for model calibration. In this way, the reliability of the trip matrix built on the basis of SIM card movement data was confirmed. This creates the possibility to use such data for the purposes of reconstruction of trip matrices for the respective pandemic stages.

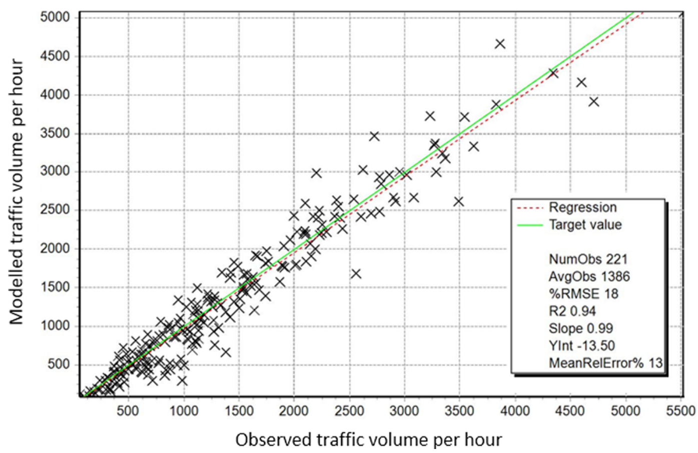

Fig. 1. Results of calibration of the model developed based on SIM card movements. Car traffic flows in the morning peak hour in 2019

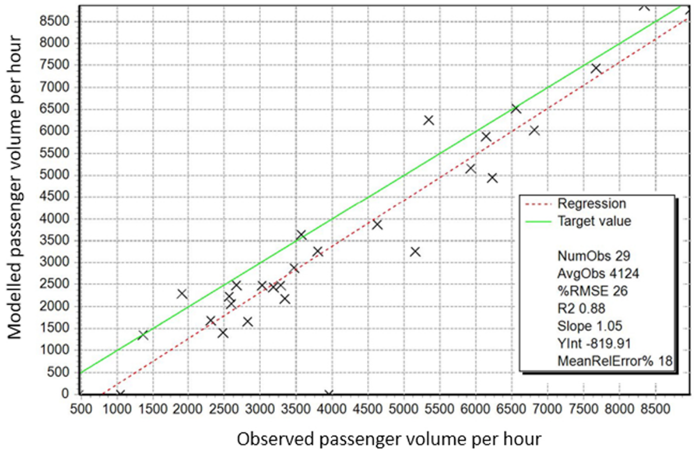

Fig. 2. Results of calibration of the model developed based on SIM card movements. Number of passengers at metro stations in the morning peak hour in 2019

Table 2. Comparison of the number of trips in the morning peak hour in 2019 obtained based on household survey and SIM cards

	Model developed based on household travel survey [18]	**Model developed based on SIM card movements**
Number of car trips	318 070	361 480
Number of public transport trips	294 826	268 075
Total number of trips	612 896	629 555
Share of car trips	0.52	0.57
Share of public transport trips	0.48	0.43

5. Social costs of introduction and relaxation of restrictions during the pandemic

The Covid-19 pandemic has brought about many changes to the economy and social life in Poland. These changes have also affected to a large extent both private and public transport by changing the associated social costs, compared to the pre-pandemic times.

The authors used the calculation methods presented above to model travel behaviour before and during the pandemic in order to evaluate the exact extent of changes of those costs. For that purpose, a standard methodology used in the analyses of social costs and benefits (Cost-Benefit Analysis) [24, 25] was applied and adapted to the specificity and scope of the data available. In Poland, the basic handbook for such analyses is 'Niebieska Księga' [26]. It defines both the methodology and unit costs of economic impact and its use is recommended in the analyses of transportation social costs and benefits.

To assess the social costs of individual mobility restrictions brought about by the pandemic, four transportation system operation periods were compared: 2019 as a pre-pandemic reference, with phases 1, 2 and 3 in 2020 (post-restriction situation). As it was necessary to examine comparable situations, the analyses of all those periods make use of traffic data obtained from the WMA transportation model in the morning peak hour developed based on the SIM card data. The model estimated trips made by cars and by all public transportation subsystems (buses, trams, metro and suburban railway).

Table 3 presents results obtained from the public transport model. The adoption of different W0 reference periods for phase 1 and phases 2 and 3 results from a significant change in the transportation system which occurred between 2019 and 2020, that is extension of the second line of the Warsaw metro. In spring 2019, that line transported passengers between Dworzec Wileński and Rondo Daszyńskiego stations. In the autumn 2019, a new section was opened – from Dworzec Wileński to Trocka station. The next extension – that of the western section ending with Księcia Janusza station – took place during the pandemic. This caused the need to define reference periods in such a way that the opening of new metro sections was taken in consideration in terms of its impact on the city transportation system. Hence, two W0 reference periods were defined:

– For phase 1 ($W0_1$), where the trip matrix from 2019 was assigned to the metro network after the start of the section ending at Trocka station, yet before the opening of the western section ending at Księcia Janusza station,
– For phases 2 and 3 ($W0_{2-3}$) with the western metro section already in operation.

Table 3. Data used in the analysis of social costs, obtained from the public transportation model for the morning peak hour

Performance data	$W0_1$	Phase 1	$W0_{2-3}$	Phase 2	Phase 3
Number of trips	267 621	89 108	268 075	86 963	154 797
Passenger-kms	2 806 709	752 189	2 815 379	760 113	1 460 605
Passenger-hours	175 845	51 699	175 534	51 264	95 644
Vehicle-kms	42 223	42 223	42 355	42 355	42 355
Average trip duration [min]	39.4	34.8	39.3	35.4	37.1
Average trip distance [km]	10.5	8.4	10.5	8.7	9.4
Average travel speed [km/h]	16.0	14.5	16.0	14.8	15.3

Table 4 includes similar performance data for private transport. Because of the limitations of data on SIM card movements it was impossible to identify the type of vehicle for private transport trips. Hence, it was assumed in the analysis that the performance data obtained from the model, expressed in vehicle-kms, refers exclusively to passenger cars. It is an assumption that puts the results of the analyses on the safe side, because unit operating costs of passenger cars are lower than those of the other types of private transport vehicles (delivery vans, trucks and buses).

A conclusion can be drawn from the data presented in Tables 3 and 4 that as a result of the restrictions imposed and changes in travel behaviour, the total number of trips, average trip

Table 4. Data for economic analyses generated by the private transport model for the morning peak hour

Performance data	**W0$_1$**	**Phase 1**	**Change**	**W0$_{2-3}$**	**Phase 2**	**Change**	**Phase 3**	**Change**
Number of trips	361 946	283 222	–22%	361 480	284 219	–21%	324 645	–10%
Passenger-km	5 506 820	3 732 510	–32%	5 499 183	3 922 939	–29%	4 861 378	–12%
Passenger-hour	152 799	83 845	–45%	152 179	88 138	–42%	116 177	–24%
Vehicle-km	3 817 009	2 703 231	–29%	3 811 601	2 839 920	–25%	3 515 914	–8%
Average trip duration [min]	25.3	17.8	–30%	25.3	18.6	–26%	21.5	–15%
Average trip distance [km]	15.2	13.2	–13%	15.2	13.8	–9%	15.0	–1%
Average travel speed [km/h]	36.0	44.5	24%	36.1	44.5	23%	41.8	16%

duration and average trip length have all decreased, which resulted in a decrease in transport operations measured in vehicle-kms and vehicle-hours. To estimate social costs, changes in transport operations were calculated between a given stage (phase 1, 2 and 3) and the respective reference period (W0$_1$ for phase 1 and W0$_{2-3}$ for phases 2 and 3). This made it possible to identify user benefits, measured as the reduction of the following costs: vehicle operating costs, travel time costs, climate impact costs (caused by greenhouse gas emitted by transport), as well as costs of air pollution, noise impact and accidents.

Because of the specific character of each transport type and different impact of the pandemic, a different methodology was adopted for private and public transport. In private transport modes, an additional effect of reduction in the number of trips was an increase in the average speed of vehicles, which contributed to further decrease of the number of vehicle-hours. At the same time, the number of vehicle-kms decreased as a result of the reduced number of trips. For public transport, it was assumed that the rolling stock transport operation in phases 1, 2 and 3 did not change with respect to 2019. Public transport had to provide a similar offer despite significantly reduced demand, resulting from the limits imposed on the vehicle occupancies (up to 30% of all the seats in a vehicle). As a result, only social benefits (measured by the difference of social costs in the respective reference period and in phases 1, 2 and 3) resulting from the reduced travel time were assessed, because the other elements of the benefits depend on changes in the rolling stock operation. Social benefits for private transport (PrT) and public transport (PuT) determined for the morning peak hour are presented in Table 5 and in Fig. 3. It must be emphasized that the benefits presented are specific to the urban passenger transport only, because in other sectors of economy a decreased number of trips caused by pandemic restrictions could result in increased social costs, e.g. through lower work efficiency. That aspect, however, is beyond the scope of the analyses performed.

Table 5. Social benefits of transport under the pandemic determined using the model developed for the morning peak hour [thousand PLN]

Category of benefits	**Phase 1**			**Phase 2**			**Phase 3**		
	PrT	**PuT**	**Total**	**PrT**	**PuT**	**Total**	**PrT**	**PuT**	**Total**
Vehicle operations	964	0	964	846	0	846	278	0	278
Travel time	2 690	4 860	7 550	2 499	4 865	7 364	1 407	3 127	4 534
Climate impact	49	0	49	43	0	43	17	0	17
Air pollution impact	159	0	159	141	0	141	54	0	54
Noise impact	65	0	65	57	0	57	17	0	17
Accidents	147	0	147	128	0	128	39	0	39
Total	**4 073**	**4 860**	**8 933**	**3 715**	**4 865**	**8 580**	**1 813**	**3 127**	**4 940**

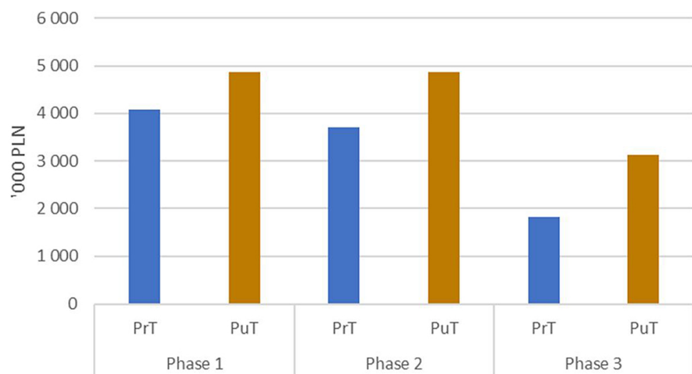

Fig. 3. Social benefits associated with transport under the pandemic, determined using the model developed for the morning peak hour

Although they show the scale of the phenomenon, the results obtained do not present the full picture of the impact on transport performance, because they take into account the general reduction of the number of trips in phases 1, 2 and 3 (year 2020) with respect to the reference period (year 2019). This results in lower social benefits in phase 3 compared to the previous phases, being a consequence of the higher number of trips. To perform the comparison excluding that effect, transport-related social costs were calculated in each case per trip. In this way, the extent of changes caused by the increased speed of travel instead of the change in trip numbers could be assessed. The calculation results are presented in Table 6 and in Fig. 4.

Table 6. Changes of transport-related social costs per trip

Cost element	**$W0_1$ [PLN]**	**Phase 1 [PLN]**	**Change**	**$W0_{2-3}$ [PLN]**	**Phase 2 [PLN]**	**Change**	**Phase 3 [PLN]**	**Change**
Vehicle operation	8.81	7.86	–10.8%	8.81	8.23	–6.6%	8.95	1.6%
Travel time (PrT)	2.31	1.62	–29.9%	2.30	1.70	–26.1%	1.96	–14.8%
Travel time (PuT)	3.60	3.18	–11.7%	3.59	3.23	–10.0%	3.39	–5.6%
Climate impact	0.41	0.35	–14.6%	0.41	0.37	–9.8%	0.40	–2.4%
Air pollution impact	1.34	1.15	–14.2%	1.34	1.21	–9.7%	1.32	–1.5%
Noise impact	0.62	0.56	–9.7%	0.62	0.58	–6.5%	0.63	1.6%
Accidents	1.39	1.26	–9.4%	1.39	1.32	–5.0%	1.43	2.9%
Total	**18.48**	**15.98**	**–13.5%**	**18.46**	**16.63**	**–9.9%**	**18.09**	**–2.0%**

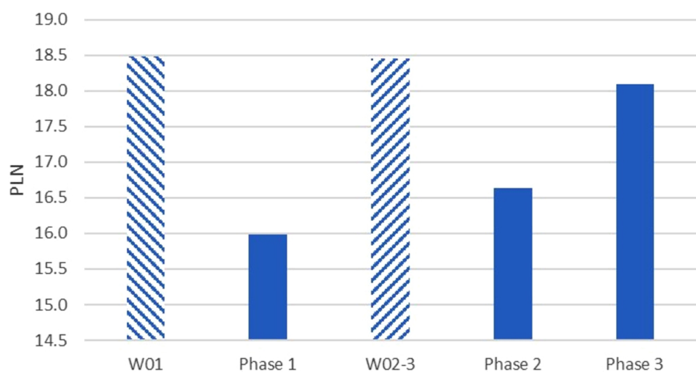

Fig. 4. Transport social costs per trip

The results presented demonstrate that the biggest reduction of the trip cost can be observed for private (individual) transport, as for phase 1 it amounts to as much as 30%. It is a consequence of the reduced number of cars on the roads and, as a result, increased average travel speed. In phase 1, the general reduction of social costs per trip as compared to the pre-pandemic period amounted to 13.5%. In the subsequent phases, the reduction was lower and amounted to 9.9% in phase 2 and to 2.0% in phase 3.

In the case of public transport another analysed aspect was an increase of the costs of transporting one passenger, borne by the transport provider. That increase resulted from the reduced passenger demand, with the rolling stock operations left unchanged. The authors considered these costs in the main subsystems of public transport in Warsaw – that is metro, tram and bus. As the presented rolling stock operations correspond to the data generated by the transport model, they do not reflect the total vehicle operating costs, which also include costs of technical runs. The calculation results can be found in Table 7 and in Fig. 5.

Table 7. Comparison of the costs of transporting one passenger over 1 km distance, borne by the transport provider (City of Warsaw) in each mode of transport in each period

Transport modes	**W0$_1$**	**Phase 1**		**W0$_{2-3}$**	**Phase 2**		**Phase 3**	
	[PLN]	**[PLN]**	**Change**	**[PLN]**	**[PLN]**	**Change**	**[PLN]**	**Change**
Metro	0.04	0.24	+500%	0.04	0.24	+500%	0.11	+175%
Tram	0.34	1.28	+276%	0.35	1.35	+286%	0.65	+86%
Bus	0.28	0.93	+232%	0.28	0.92	+229%	0.50	+79%

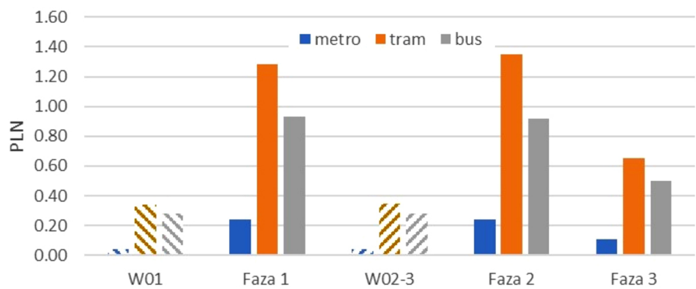

Fig. 5. Costs of transporting one passenger over a distance of 1 km borne by the transport provider (City of Warsaw)

The results show, therefore, that the pandemic has caused a very high increase in the unit costs of transporting passengers from the public transport provider's point of view. In case of metro, the costs increased as much as 6 times.

6. Discussion of the results

The pandemic effects for Warsaw determined in this research are comparable to those in other cities and countries, as reported in the literature. In Switzerland and Germany, the general number of trips dropped at the stages of the strictest restrictions by 60%, whereas in Sweden, where there was practically no lockdown, by 40%. In Warsaw the number of domestic long-distance trips to the capital city went down by about 75%, while that of intra-city trips – by about 25%, and trips from suburban areas – by 32%. That percentage was even higher in the morning rush hours when it amounted to 45–47% for trips inside of the city and to 52–54% for trips made from suburban areas. The capital of Poland did better than Rome where the total number of trips dropped by more than 75%. It might have resulted from a less serious epidemiological situation in Poland than in Italy or it might have been related to tourist trips which basically stopped during the strictest anti-COVID-19 measures and which before the pandemic had been more numerous in Rome than in Warsaw.

Transportation models were developed for the purposes of estimating social costs associated with the impact of the pandemic on the performance of passenger transport in the city. Their application has shown that during restrictions and mobility limitations in the Warsaw urban transport system, social benefits occurred due to shorter duration of trips and reduced vehicle operating costs. The benefits resulted mainly from the reduced number of trips in the morning rush hours – by 10–22% (depending on the period) for private transport and by 42–67% for public transport. Social costs calculated per trip were also lower by 13.5% in phase 1, by 9.9% in phase 2, and by 2.0% in phase 3, compared to the pre-pandemic situation. However, in the case of public transport, a very high increase was observed in the costs of one passenger-km born by the transport provider and, as a result, a decrease of the system economic efficiency occurred. This increase was particularly high for rail transport – metro and trams.

7. Conclusions and directions for further work

As a part of the IDUB project, transportation models were developed to make it possible to assess the consequences of the COVID-19 pandemic on the performance of the urban passenger transport system. The models can contribute to an improvement of response to society demand for mobility during a pandemic.

The possibility to effectively use Big Data (movements of SIM cards shared by mobile network operators) for the purposes of building transportation models under highly unusual circumstances (e.g. significant changes in mobility resulting from restrictions imposed at the time of the pandemic) was confirmed as well and the possibility to reconstruct such situations *post factum*. It was also possible to compare the conditions of operation of transport systems before and during the pandemic.

The analysis of data on SIM card movements also demonstrated the possibility to use this type of data to assess the situation and the extent of changes in travel behaviour of city residents. Individual mobility data collected in this way confirmed the expectations as to the travel effects of restrictions implemented during the successive pandemic phases.

References

[1] *Road Safety Annual Report 2021: the Impact of Covid -19. OECD Publishing*, Paris: ITF, 2021.

[2] A. Brzeziński and T. Dybicz, "Possibility of Big Data application for OD-Matrix calibration in transport demand models", *Archives of Civil Engineering*, vol. 67, no. 1, pp. 215–232, 2021, doi: 10.24425/ace.2021.136470.

[3] P. Szrywer, J. Wachnicka, W. Kustra, and O. Pellegrino, "Study on the prevalence of mobile use by car drivers – the case of Poland", *Archives of Civil Engineering*, vol. 67, no. 4, pp. 225–242, 2021, doi: 10.24425/ace.2021.138496.

[4] K.T.V.K Reddy and S.P. Challagulla, "Travel data collection using a smart phone for the estimation of multimodal travel times of intra-city public transportation", *Archives of Civil Engineering*, vol. 68, no. 3, pp. 397–409, 2022, doi: 10.24425/ace.2022.141893.

[5] A. Brzeziński and A. Waltz, "Construction of the passenger rail traffic generation model", *Archives of Civil Engineering*, vol. 68, no. 3, pp. 107–123, 2022, doi: 10.24425/ace.2022.141876.

[6] A. Aloi, B. Alonso, J. Benavente, et al., "Efects of the COVID-19 Lockdown on Urban Mobility: Empirical Evidence from the City of Santander", *Sustainability*, vol. 12, no. 9, art. no. 3870, 2020, doi: 10.3390/su12093870.

[7] P. Bucsky, "Modal share changes due to COVID-19: The case of Budapest", *Transportation Research Interdisciplinary Perspectives*, vol. 8, art. no. 100141, 2020, doi: 10.1016/j.trip.2020.100141.

[8] E. Jenelius and M. Cebecauer, "Impacts of COVID-19 on public transport ridership in Sweden: Analysis of ticket validations, sales and passenger counts", *Transportation Research Interdisciplinary Perspectives*, vol. 8, art. no. 100242, 2020, doi: 10.1016/j.trip.2020.100242.

[9] C. Eisenmann, C. Nobis, V. Kolarova, B. Lenz, and C. Winkler, "Transport mode use during the COVID-19 lockdown period in Germany: The car became more important, public transport lost ground", *Transport Policy*, vol. 103, pp. 60–67, 2021, doi: 10.1016/j.tranpol.2021.01.012.

[10] J. Molloy, T. Schatzmann, B. Schoeman, C. Tchervenkov, B. Hintermann, and K.W. Axhausen, "Observed impacts of the Covid-19 first wave on travel behaviour in Switzerland based on a large GPS panel", *Transport Policy*, vol. 104, pp. 43–51, 2021, doi: 10.1016/j.tranpol.2021.01.009.

[11] P. Borkowski, M. Jażdżewska-Gutta, and A. Szmelter-Jarosz, "Lockdowned: Everyday mobility changes in response to COVID-19", *Journal of Transport Geography*, vol. 90, art. no. 102906, 2021, doi: 10.1016/j.jtrangeo.2020.102906.

[12] A. Przybylowski, S. Stelmak, and M. Suchanek, "Mobility Behaviour in View of the Impact of the COVID-19 Pandemic – Public Transport Users in Gdansk Case Study", *Sustainability*, vol. 13, no. 1, art. no. 364, 2021, doi: 10.3390/su13010364.

[13] F. Schlosser, B.F. Maier, O. Jack, and D. Brockmann, "COVID-19 lockdown induces disease mitigating structural changes in mobility networks", *PNAS*, vol. 117, no. 52, 2020, doi: 10.1073/pnas.2012326117.

[14] C. Chivers, "How COVID-19 is affecting public transit use", *CBC News,* 2020. [Online]. Available: https://www.cbc.ca/news/canada/coronavirus-covid19-public-transit-1.5509927.

[15] S. Jeffords, "Transit ridership, revenue in steep decline during COVID-19 pandemic". *Toronto: The Canadian Press*, 2020. [Online]. Available: https://nationalpost.com/pmn/news-pmn/canadanews-pmn/go-transit-ridership-down-90-per-cent-as-people-stay-home-during-pandemic.

[16] T. Hughes, "Poor, essential and on the bus: Coronavirus is putting public transportation riders at risk". *USA TODAY*, 2020. [Online]. Available: https://eu.usatoday.com/story/news/nation/2020/04/14/public-transportation-users-risk-coronavirus-spreads-across-us/2979779001/.

[17] M. de Haas, R. Faber, and M. Hamersma, "How COVID-19 and the Dutch 'intelligent lockdown' change activities, work and travel behaviour: Evidence from longitudinal data in the Netherlands", *Transportation Research Interdisciplinary Perspectives*, vol. 6, art. no. 100150, 2020, doi: 10.1016/j.trip.2020.100150.

[18] K. Gkiotsalitis and O. Cats, "Public transport planning adaption under the COVID-19 pandemic crisis: literature review of research needs and directions", *Transport Reviews*, vol. 41, no. 3, pp. 374–392, 2020, doi: 10.1080/01441647.2020.1857886.

[19] A. de Mauro, M. Greco, and M. Grimaldi, "A Formal definition of Big Data based on its essential Features", *Library Review*, vol. 65, no. 3, pp. 122–135, 2016, doi: 10.1108/LR-06-2015-0061.

[20] *Zachowania transportowe warszawiaków w dobie koronawirusa – raport z badania.* The Capital City of Warsaw, 2020.

[21] A. Brzeziński, K. Brzeziński, P. Dąbkowski, T. Dybicz, K. Jesionkiewicz-Niedzińska, Ł. Szymański, and P. Włodarek, "The application of a logistic regression model for predicting preferences of transport system users", *Archives of Civil Engineering*, vol. 64, no. 4, pp. 145–159, 2018, doi: 10.2478/ace-2018-0049.

[22] *Warszawskie Badanie Ruchu 2015 wraz z opracowaniem modelu ruchu.* The Capital City of Warsaw, 2016.

[23] A. Brzeziński, T. Dybicz, and Ł. Szymański, "Zasady prognozowania ruchu drogowego z uwzględnieniem innych środków transportu". DZP/RID-I-62/11/NCBR/2016 – raport z pracy badawczej. Politechnika Warszawska, 2019.

[24] A.E. Boardman, D.H. Greenberg, A.R. Vining, and D.L. Weimer, *Cost-Benefit Analysis: Concepts and Practice,* 2nd ed. Upper Saddle River, New Jersey: Prentice Hall, 2001.

[25] J. Dyduch, "Wykorzystanie analizy kosztów i korzyści do oceny projektów inwestycyjnych", *Ekonomia Menedżerska*, no. 10, pp. 95–108, 2011.

[26] *The Blue Book*, *Niebieska Księga. Sektor Transportu Publicznego w miastach, aglomeracjach, regionach (Blue Book. Sector of public transport in cities, metropolitan areas and regions)*. Jaspers, 2015 (in Polish).

Szacowanie kosztów społecznych wynikających ze zmian mobilności spowodowanych pandemią COVID-19

Słowa kluczowe: pandemia COVID-19, modelowanie podróży, mobilność, koszty społeczne, transport publiczny, Big Data

Streszczenie:

Pandemia COVID-19 wywołała wiele zmian w funkcjonowaniu gospodarki oraz życia społecznego. Dotyczyło to w dużej mierze transportu, zarówno indywidualnego, jak i zbiorowego. Zmieniły się wzorce mobilności mieszkańców miast na całym świecie. Zmiany te dotyczyły liczby odbytych przejazdów, czasu ich trwania i kierunków, a także wybieranych środków transportu. Zmiany mobilności były powodowane strachem przed podróżowaniem w zatłoczonych pojazdach i zakresem ograniczeń wprowadzonych przez rządy. Skutki takich zmian są trudne do oszacowania, a ich ocena jest zagadnieniem złożonym. W ramach pracy badawczej "Method of assessing the social impact of changes in personal mobility in an epidemic state together with tools to support transport management" będącej częścią programu "IDUB against COVID" realizowanego w Politechnice Warszawskiej podjęto próbę zbudowania modeli obliczeniowych odwzorowujących zachowania transportowe sprzed i w czasie pandemii. To z kolei umożliwiło oszacowanie wielkości zmian kosztów społecznych pandemii, przy zastosowaniu standardowej metodyki wykorzystywanej w analizach kosztów i korzyści społecznych (AKK), z dostosowaniem jej do charakteru i zakresu danych, którymi dysponowano. Porównano dwa okresy funkcjonowania systemu transportowego: rok 2019, traktując go jako okres odniesienia przed pandemią, z okresem pandemii, wiosną 2020 (sytuacja po wprowadzeniu obostrzeń). Ze względu na konieczność badania porównywalnych sytuacji, w analizach obu okresów opracowano multimodalne (ruch samochodowy i transport zbiorowy) modele podróży dla Warszawy dla godziny szczytu porannego. Tworząc modele posługiwano się dostępnymi danymi o sieci transportowej oraz pomiarami ruchu, uzupełnianymi danymi o przemieszczeniach kart SIM, pozyskanymi od operatora telefonii komórkowej. Obliczenia pozwoliły ocenić koszty społeczne pandemii związane z systemem transportu miejskiego, spowodowane głównie zmianami w korzystaniu z transportu prywatnego i publicznego. Przeprowadzone analizy potwierdziły, że w efekcie wprowadzonych obostrzeń w mobilności oraz zmian zachowań komunikacyjnych nastąpiło ogólne zmniejszenie liczby podróży, co w konsekwencji doprowadziło do zmniejszenia prac przewozowych mierzonych w pojazdo-km i pojazdo-godz. Zmiany te obliczano jako różnice pomiędzy fazą pandemii a okresem odniesienia (ten sam okres rok wcześniej). Umożliwiło to wyznaczenie korzyści użytkowników stanowiących redukcję kosztów: czasu pasażerów, eksploatacji pojazdów, wypadków, zanieczyszczenia powietrza, zmian klimatycznych i oddziaływania hałasu.

Ze względu na specyfikę poszczególnych środków transportu i odmienny wpływ pandemii, zastosowano zróżnicowaną metodykę w odniesieniu do transportu indywidualnego i zbiorowego. W transporcie indywidualnym dodatkowym efektem zmniejszenia liczby podróży był wzrost średnich prędkości pojazdów, co przyczyniło się do dalszego zmniejszenia liczby pojazdo-godzin. Jednocześnie, w konsekwencji zmniejszenia liczby podróży, zmniejszyła się liczba pojazdo-km. W odniesieniu do transportu zbiorowego

założono, że praca przewozowa taboru nie uległa zmianie w porównaniu do okresu przed pandemią. Transport zbiorowy musiał zapewniać zbliżoną ofertę przewozową, pomimo znacznie zmniejszonego zapotrzebowania, będącego efektem wprowadzenia limitów osób w pojazdach. W konsekwencji, oszacowane korzyści społeczne (mierzone różnicą kosztów społecznych w okresie pandemii i przed pandemią) w transporcie zbiorowym wynikały głównie z oszczędności czasu przejazdu. Uzyskane wyniki pokazały skalę zjawiska zmian w mobilności wywołanych pandemią. Stwierdzono, że w okresie występowania ograniczeń mobilności, w warszawskim systemie transportu miejskiego wystąpiły korzyści społeczne wynikające z krótszego czasu trwania przejazdów i obniżenia kosztów eksploatacji pojazdów. Korzyści wynikały przede wszystkim ze zmniejszenia liczby podróży w godzinach porannego szczytu – o 10–22% (w zależności od okresu) w przypadku transportu samochodowego i o 42–67% w przypadku transportu zbiorowego. Koszty społeczne pojedynczej podróży były również (nawet o 13,5%) niższe w porównaniu z sytuacją sprzed pandemii. Natomiast w przypadku transportu zbiorowego zaobserwowano bardzo duży wzrost kosztów jednego pasażerokilometra, ponoszonych przez przewoźników i w efekcie spadek efektywności ekonomicznej systemu. Wzrost ten był szczególnie wysoki w przypadku transportu kolejowego – metra i tramwajów (w przypadku systemu metra prawie 4–5 krotny!). Potwierdzono również możliwość efektywnego wykorzystania Big Data (przemieszczenia kart SIM) na potrzeby budowania modeli transportowych w bardzo nietypowych okolicznościach (np. istotnych zmianach mobilności wynikających z ograniczeń nałożonych w czasie pandemii) oraz możliwość rekonstrukcji takich sytuacji post factum. Możliwe było również porównanie warunków funkcjonowania systemów transportowych przed i w trakcie pandemii. Analiza danych o przemieszczeniach kart SIM wykazała możliwość wykorzystania tego typu danych do oceny sytuacji i zakresu zmian zachowań podróżujących mieszkańców miast. Zebrane w ten sposób indywidualne dane dotyczące mobilności potwierdziły oczekiwania co do wpływu na mobilność ograniczeń wprowadzanych w kolejnych fazach pandemii.

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