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Perspectives of the use of smartphones in travel behaviour studies: Findings from a literature review and a pilot study

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ABSTRACT

Human travel behaviour has recently been one of the most popular topics in transport studies. Therefore, the ability to obtain valuable sets of data has become one of the key challenges for researchers. Traditional mobility surveys have many important limitations. In this situation, the potential of the use of smartphones and dedicated applications in the identification of individual travel behaviour seem very promising. We set ourselves a goal to indicate strengths and weaknesses of data obtained with this method and assess the perspectives of its use for the needs of public policies. For these purposes we prepared a low-cost mobile application and conducted a pilot study among students in Poznań (Poland). In effect, trajectories of more than 100 people with almost 3 billion of location data were collected. Based on a literature review and our results we discuss the main problems, limitations and challenges of the broader use of the data obtained with smartphones. In the conclusion, we argue that there is a huge and increasing potential connected with mobile phones, but still some important barriers exist including sampling problems, limitations in big data analyses and technological issues. Therefore, a broader use of smartphones in travel behaviour surveys seems to be rather a distant perspective.

1. Introduction

The appearance and development of time-geography popularised by Torsten Hägerstrand (1970, 1985) changed the perception of transport systems. As a result, since the 1970s analyses on human travel behaviour (an activity-based approach) have become one of the most popular topics in transport studies (Jones et al., 1983; Fox, 1995; Buliung and Kanaroglou, 2006). Until now a plethora of studies concerning individual travel behaviour and connecting them e.g. with housing decisions, land use (or neighbourhood) characteristics, the level of accessibility of transport infrastructure and so on have been undertaken. Moreover, we should also notice the increasing role of travel behaviour studies in public policies (Fox, 1995). According to Marshall (2001), in the last decades there has been a shift from a conventional approach to transport planning where the focus was on traffic and 'travel as a derived demand' to a new approach in which people are in the centre of interest and travel is treated also as a valued activity. Therefore, nowadays the identification of travel behaviour (e.g. such elements as travel motivations of inhabitants, popular destinations, movement directions, a mode selection) is often the starting point for the reflection on the future development of transport systems. This information could be used to identify current and to predict future travel demand for infrastructure investment and policy decisions (Kitamura et al., 1997, 2000; Pendyala et al., 1997). This is particularly important in densely populated areas where travel patterns are very complicated – this usually causes numerous problems and challenges (congestion, pollution, noise, accidents – see Banister, 2011).

But still – since the 1970s – one of the key challenges to studies on human travel behaviour has been the ability to obtain valuable

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sets of data (McNally and Rindt, 2007). Until now the basic sources of data in many studies are surveys with the use of travel diaries and questionnaires (paper-and-pencil or web-based). However, we should note that these traditional surveys have some important limitations. First of all, travel diaries are not a very efficient method of collecting data. They require a lot of commitment from the participants (Duncan and Mummery, 2007). Relatively high is the risk that a respondent can forget to provide some information (Gould, 2013). Data accuracy can be also relatively low (especially when the information about a trip is entered in a travel diary several hours after the trip) and finally, it is hard to retrace actual travel routes and some precise information (e.g. the speed of travel). In the case of surveys with questionnaires, a common problem is that they generally contain data on regular travel behaviour. Moreover, the meaning of 'regular' is very subjective and very often the number of questions has to be limited (due to the costs and to shorten the time needed to fill the questionnaire). Therefore, the identification of very detailed travel behaviour of an individual with the use of traditional questionnaires is quite difficult (Clifton and Handy, 2003). On the other hand, the main advantage of this method is its easiness and the possibility to collect the opinions of many respondents in a relatively short time and at a reasonable cost. Therefore, surveys with traditional questionnaires remain the basic method used in mobility studies. Unfortunately, they usually provide highly generalized information on travel behaviour and are not sufficient for in-depth studies (Wolf, 2000; Shen and Stopher, 2014).

These limitations of traditional mobility surveys caused the increasing interest in the studies with the use of new automatic and more efficient methods of data collection in recent years. The use of data from GPS devices, mobile phones, smart cards, social media are becoming more and more popular. Their main advantage is the automatic collection of a huge amount of data (big data) on spatiotemporal trajectories, popularly selected locations, travel origins and destinations, and so on (Vij and Shankari, 2015; Chen et al., 2016). They allow gathering large sets of data without time-consuming and expensive surveys. Yue et al. (2014, p. 72) conclude: "these data help us to understand human travel behaviour better by zooming more closely into individuals than ever". Therefore, in the last years a great number of studies from different scientific disciplines have appeared. We could find examples of papers on tourism (Kotus et al., 2015), sociology (Eagle et al., 2009; Picornell et al., 2015), or even ethnography (Christensen et al., 2011) where big data were used to identify behaviour of humans. No doubt, the use of this type of data in transport studies is the most common.

The most popular automatic method of obtaining big data on travel behaviour of individuals seems to be from GPS devices (Yue et al., 2014). In our opinion, however, a huge and still increasing potential is connected with mobile phones, now commonly equipped with GPS modules and other sensors (providing so-called assisted GPS data). Therefore, in this paper we would like to assess the potential of the use of smartphones and dedicated applications in the identification of individual travel behaviour. We set ourselves a goal to indicate strengths and weaknesses of data obtained with this method and to discuss the perspectives of its use in travel behaviour studies. For this purpose we prepared a low-cost mobile application and conducted a pilot study among students in Poznań (Poland).

The construction of the paper is as follows. After the introductory part, a literature review is included. In this section we focus on advantages and disadvantages of both GPS devices and mobile phones and also present a few transport studies concerning the use of applications dedicated to smartphones. In the next part the construction of the pilot study is presented. We describe our mobile application, the study area and some problems with sampling. Then we present our experiences related to the research organisation and observations of the participants. The final part consists of a discussion and a short summary.

2. Literature review – The use of GPS devices and mobile phones in transport studies

2.1. GPS location data

The first studies in transport geography with the use of GPS devices appeared in the mid-1990s. One of the precursor studies was conducted by the researchers from the University of South Australia (Zito and Taylor, 1994; Zito et al., 1995) who propose methods of locating and monitoring vehicles in real time across a road network with the use of GPS data. The first studies on a broader scale concerning human travel behaviour were conducted in Lexington, Kentucky in 1996 (Wagner, 1997) and Austin, Texas in 1997 (Pearson, 2001). In the next years, the popularity of GPS data in such studies increased rapidly (e.g. Murakami and Wagner, 1999; Sermons and Koppelman, 1996). Nowadays GPS devices have become the most widely used sources of trajectory data (Yue et al., 2014). One of their main advantages is a high quality of locational data, which are very precise (to within a few metres), offer high recording frequency and could be used to assess the speed and direction of an equipped individual or vehicle (Duncan et al., 2009; Smoreda et al., 2013). Therefore, GPS devices are commonly used in studies on traffic demands, travel chains, sustainable mobility, traffic safety, route choice and residential selection (Shen and Stopher, 2014). In some cases they were also used as supplementary surveys to measure the accuracy of traditional ones.

According to Vlassenroot et al. (2015), the great popularity of GPS data in transport studies was caused also by the fact that GPS devices are commonly installed in public transport vehicles. Their role is to provide real time information on the location of buses, trams or trains and they are commonly employed in passenger information systems. Based on GPS data from public transport vehicles several studies concerning speed diagnoses (Tantiyanugulchai and Bertini, 2003; Cortés et al., 2011), path and travel time (Hunter et al., 2009) or service reliability (Mazloumi et al., 2009) were developed. In the last years, there have also appeared bike-sharing systems in which the location of a particular bicycle is provided by the GPS tracking system. Such data enables complex analyses on cyclist behaviour (e.g. Reiss et al., 2015). Unfortunately, GPS devices installed in vehicles show the movement behaviour of individuals only when a vehicle is used. Therefore, only a unimodal part of an individual's trip behaviour can be covered (Vlassenroot et al., 2015).

Despite their high popularity in transport studies, GPS devices have also their commonly known disadvantages. First of all, the process of data collection requires a dedicated device (GPS data logger). Its price is much lower than at the end of the 20th century, but still (especially in extensive surveys with many respondents) it can be a significant expense (Wolf, 2006; Zhao et al., 2015). Moreover, such a handheld device requires effort and discipline from respondents who should carry it with them, recharge or change batteries, and in some cases also make some operations (Smoreda et al., 2013; Vlassenroot et al., 2015).

Secondly, we should also mention some technical limitations to the use of GPS devices. The main problem is connected with a possible loss of the satellite signal. This situation could be quite common in buildings, vehicles, underground passages or even in densely built-up areas (so called ‘an urban canyon effect’ – see Stopher et al., 2008; Gong et al., 2012). What is more GPS receivers consume considerable amount of energy. According to (Smoreda et al., 2013, p. 764) “it is difficult to follow a person for more than one day without needing to recharge its battery”. It increases costs and requires great engagement from respondents. Of course, some of these limitations could be reduced when using technically advanced but expensive GPS devices.

Finally, there is also a significant collection of travel behaviour data which could not be obtained with GPS devices. Although there are (imperfect) methods of an automatic detection of the transport mode (with the accuracy of about 90%) or travel purposes (with 40–97% accuracy – see Shen and Stopher, 2014; Ermagun et al., 2017), GPS log data lack socio-demographic information, human motivations and feelings. Therefore, additional methods of data collection (requiring interaction with the respondent) are often used in travel behaviour studies together with GPS devices (Cottrill et al., 2013). The most popular are still paper-based techniques, but additional data are collected more and more often with the use of dedicated websites (Li and Shalaby, 2008; Greaves et al., 2010). The main drawback is the fact that this additional information in many cases has to be reconstructed in retrospect (Vlassenroot et al., 2015).

2.2. Mobile phones

In the last years mobile phones have started to be perceived as promising tools for obtaining data for travel behaviour analyses. Yue et al. (2014, p. 72) enthusiastically note that “the most unique and fascinating feature of mobile phone data is their prevalent scale, which provides longitudinal and individual details for microscope research” and “the overwhelming sampling penetration of the entire population has never been achieved by previous travel behaviour studies”. Recently a mobile phone has become one of the essential objects that people take when they leave home (Cui et al., 2007). As a constant companion of people, it seems to have a great potential for the use in surveys on travel behaviour. Therefore, in the last years we could notice a rapid increase in the number of studies with the use of mobile phone data. There definitely dominate surveys with the use of cell-tower-based data collected within the phone network and obtained from mobile operators (Azam et al., 2012, Chen et al., 2014, Järv et al., 2014; Çolak et al., 2015; Picornell et al., 2015). Their main advantage is passive data collection (automatically recorded without bothering users). This fact makes it possible to conduct longitudinal travel surveys on a very large user population in a wide area. On the other hand, cell-tower-based data do not provide such information as reasons for travel, modes of transport, stops, and personal characteristics (Smoreda et al., 2013). Their accuracy is also relatively low.

Solving these problems became possible with the development of the so-called assisted global positioning system (A-GPS), which uses both GPS and a terrestrial cellular network to obtain geographic position (Spinney, 2003; Ratti et al., 2006). According to Gong et al. (2014, p. 558) “this technology can receive satisfied GPS signal inside buildings, vehicles, as well as ‘urban canyons’ in cities where tall buildings and other edifices block GPS signals”. In 2003 Spinney (2003, p. 262) noted that A-GPS technologies seem very promising, but require “costly investment for mobile networks and new infrastructure and device technology enhancements”. It seems that this technological leap has been made in the last years together with increasing cellular network performance, the development of other data transfer technologies and the popularisation of smartphones. Technologically advanced mobile phones can typically gather data from different sources: a cellular network, a GPS signal, a Wi-Fi signal, an accelerometer, the Bluetooth, and can be used almost like personal computers. Therefore, it has become possible to gather great amounts of precise location data without the use of dedicated devices (Ratti et al., 2006). Furthermore, a greater variety of location data sources helps to avoid typical problems of GPS devices with the loss of signal (in buildings, ‘urban canyons’ or during the warm-up time when finding the first position) and in consequence – with missing data. It seems that the use of mobile phones with GPS functionality in travel behaviour studies appears to combine the advantages of both GPS devices and mobile phones. What is more, smartphones can be equipped with specialized software to simplify the process of data collection or to broaden the spectrum of research (e.g. an integrated questionnaire). Gong et al. (2014, p. 558) conclude that this technology “may become the main method of personal trip data collection in the future at lower cost and with minimum burden on respondents”.

However, we should also mention some (technological) disadvantages of GPS-enabled mobile phones. First of all, the accuracy of location measurement could be slightly worse than in the case of advanced GPS devices (but still could provide quantitative travel information – Zandbergen and Barbeau, 2011; Tao et al., 2012). Shen and Stopher (2014) report also that using smartphones to obtain GPS data is limited because of a relatively short battery life and a high cost of transferring data from phones to data centres. However, it seems that these limitations are becoming less and less important together with the technological development of mobile phone networks and smartphones.

Despite these limitations, the perspectives of the use of smartphones in travel behaviour studies look optimistic. However, we could find only several examples of the implementation of this technology in travel behaviour studies. We collected studies with the use of GPS-enabled mobile phones in a Table 1. According to this review, we could distinguish two main groups of research. First of them (usually with a relatively low research sample) focus on some methodological aspects of using A-GPS data. In this case the main objective was to verify the utility of A-GPS data (Ohmori et al., 2005; Winters et al., 2008; Jariyasunant et al., 2011, 2015; Montini

Table 1
Transport studies with the use of GPS-enabled mobile phones.

Project, research area, author(s)	Data sources	Construction of the research	Sample	Identified travel characteristics
"GPS Mobile Phone-Based Data Collection System" Tokyo, Ohmori et al. (2005, 2006)	GPS signal	Java application: active logging mode, paper-based survey (to compare)	1st survey: 34 participants, 2nd survey: 13 participants	Activity type, location, travel mode, accompanied persons
TRAC-IT, Tampa, Florida Wright (2008), Barbeau et al. (2009)	GPS signal, cell towers	Pre-survey (questionnaire), active tracking mode	14 volunteers (317 trips)	Tracks characteristics, origin and destination information
'Mobile Century', Union City, California, Amin et al. (2008) and Herrera et al. (2010)	GPS signal, cell towers	Experiment with vehicles	100 vehicles carrying a GPS-enabled phone	Real-time traffic monitoring
'Quantified Traveler', San Francisco Bay, Jariyasunant et al. (2011, 2015)	GPS signal, accelerometer, WiFi, cell towers	Pre-survey (questionnaire), tracking mobile application, post-survey (questionnaire)	28 young persons (Jariyasunant et al., 2011) 135 people participated in the experiment, 118 answered both the pre- and post-survey (Jariyasunant et al., 2015)	Addresses/neighbourhoods of trips made, distance travelled, time spent traveling, CO2 emitted, calories expended, travel costs
'Real-Time Urban Traffic State Estimation', Stockholm Tao et al. (2012)	GPS signal	Microscopic traffic simulation and field tests	Number of allocated probe tracks: 63	Average road link speeds
'The Future Mobility Survey', Singapore, Cottrill et al. (2013) and Zhao et al. (2015)	Accelerometer, Wi-Fi, GSM, GPS (only in selected periods of a day)	Pre-survey (questionnaire), smartphone application (passive logging mode), web-based activity diary, post-survey (questionnaire)	74 initial persons, 34 persons installed the app and collected data, 27 persons validated their data (Cottrill et al., 2013)233 employed (full-time or part-time) participants (Zhao et al., 2015)	Distance-from-home, time of travel, travel time by mode
'Nemo-Phone', Vienna, Nitsche et al. (2014)	GPS signal, cell towers, accelerometer	Data logging application (passive), annotations on the current transport mode	15 volunteers over a period of 2 months	Detection of transport modes
'The MOVE project', Flanders, Vlassenroot et al. (2015)	GPS, cell towers, detected Wi-Fi networks, accelerometer	Smartphone application: both passive logging mode and active logging mode (diary application)	23 test persons, (2.243 trips)	Transport mode, number of trips, average speed, local activity, origin-destination relations
'Dutch Mobile Mobility Panel', Netherlands, Geurs et al. (2015)	GPS, WiFi, accelerometer and cell-ID information	Web-based prompted recall survey	600 respondents	departure and arrival times, trip origins and destinations, transport modes, travel purposes
'SmarTrAC'/'Daynamica', Minneapolis, Fan et al. (2015)	Smartphone's built-in sensors	Smartphone application (bringing together automatic sensing, surveying, and statistical machine learning)	17 real -world Android phone users	Attributes of daily activity and travel episodes (activity/trip duration, travel mode, and activity type)
"The Mobile Territorial Lab", Trentino region, Italy Centellegher et al. (2016)	GPS, cell towers, call and SMS logs	Mobile platform, additional survey application (asking questions)	142 volunteers	Parents' daily lives: social interactions, mobility routines, spending patterns,
'TRIP' Seattle metropolitan region, Woodard et al. (2017)	GPS signal	Anonymized mobile phone GPS data from Windows phones	145,657 trips	Speed of traffic, weekly cycles in congestion levels

et al., 2015; Vlassenroot et al., 2015), enhance their accuracy (Nour et al., 2016) or detect (from raw data) travel stages (Zhao et al., 2015) and transport modes (Nitsche et al., 2014).

At the same time, there are not many examples of studies where mobile phones were used on a broader scale to obtain data on the travel behaviour of people for some analytical purposes or for the needs of public policies. One of them is a survey conducted within the 'Dutch Mobile Mobility Panel' project (Geurs et al., 2015). With this initiative, authors would like to provide some evidence on factors influencing the variation in travel behaviour over time. Their first results seem promising – with a dedicated mobile application ('MoveSmarter') a wide range of travel behaviour (departure and arrival times, trip origins and destinations, transport modes, and travel purposes) of about 600 smartphone and non-smartphone owners (equipped with mobile phones for research purposes) was detected. Geurs et al. (2015, p. 247) conclude that such a survey could be "a promising alternative or addition to traditional trip diaries, reducing a respondent burden and increasing the accuracy of measurement". The other example is the survey conducted in Singapore as part of a subset of a national household travel survey by Cottrill et al. (2013). Advanced sociological surveys with the use of smartphones were also deployed in Trentino region by Centellegher et al. (2016).

Therefore, finally we come to raise an important question about the future of surveys with the use of smartphones in travel behaviour studies: are they reserved only for large-scale studies and extended research teams with a significant budget, or do they stand a chance of being also used on a broader scale in local studies and for the purposes of public policies? To answer these questions, in the next section we present our simple pilot study conducted in Poznań (Poland). Evidence from this survey should help to get a wider perspective on the utility of A-GPS data for modest surveys on travel behaviour. The above challenges will be discussed more thoroughly in the last section of this paper together with the conclusions from the pilot study conducted by the author and presented in the next sections.

3. A pilot study

3.1. Architecture of the survey

In our survey we wanted to connect advantages of both GPS devices and mobile phones and to show the potential of the use of such technologies in the identification of individual travel behaviour (for the needs of public policies). Therefore, we assumed that the survey should be characterized by: (a) simplicity and low construction costs, (b) a possibility to integrate different types of data, and (c) the relatively high accuracy of obtained data. What is more, our additional objective was to ensure the low level of the engagement of and burden for survey participants. Thus, at the stage of the survey construction we tried also to minimize the costs of a data transfer, energy consumption and the use of a phone memory (cf. Zhao et al., 2015). It was done to increase the desire to participate in the research.

Finally, we worked out the survey methodology based on an application for mobile phones and the server where the data had been gathered. A mobile application named 'TwojaTrasa' ('YourTrack') was designed for the Android system[1] and placed in popular on-line app store (Google Play). After the process of installation, a mobile phone user was asked to fill in an initial questionnaire (Fig. 1). It included questions about the gender, age, material status, education, employment as well as some questions about household (the size, legal status, and time since the last household change) and available travel modes (the number of cars, number of season tickets for public transport). Filling in the questionnaire was the last stage in which the engagement of a user was necessary. Then, the basic role of the application was to save automatically the current locations of mobile phone users. It runs in the background of a phone, collecting location data without the user's intervention (Zhao et al., 2015). Survey participants could only observe an increasing number of saved 'points' with location coordinates in 'the user's panel' (Fig. 1). Additionally, there was also a possibility to display a document with the very detailed arrangements of a privacy policy.

The main source of location data was a GPS module contained in a smartphone. They were supplemented by the data from the cellular network, Wi-Fi network and an accelerometer. This helped to avoid a permanent loss of signal in buildings, tunnels, 'urban canyons', etc. The data were saved on a phone in a 'delay tolerant' way (see Centellegher et al., 2016) and transferred to the server where the internet connection was made (for example, when a participant connected to the Wi-Fi network; the permanent internet connection was not required). Locations were saved every 30 s during the whole day. On the server such data as: XY coordinates, time, altitude, a speed of movement were gathered. The control panel (web-based map service) was also constructed to make the easy visualisation of trajectories and the monitoring of ongoing tests possible (Fig. 2).

3.2. Sample and study area

In the presented pilot study we decided to collect the travel behaviour data of students and other young adults. The main reason why we focus on students and young adults in our research is the fact that they are commonly considered as natural smartphone users (Kim et al., 2015). This supposition can be proved by the results of earlier research conducted in Poland. According to the survey from 2015 (TNS Poland, 2015), 58% of Poles owned a smartphone. In younger age groups (15–19, 20–29) this proportion was much higher (around 90%). The report 'Android in Poland (2015)' contains similar conclusions. Authors noticed that only 14% of the respondents who filled in the online questionnaire (used in this survey) were over 45 years old. Therefore, the risk of excluding a significant part of the population from the survey was relatively small.

[1] Android was the most popular operating system in Poland (it was installed in 65% of smartphones according to the TNS survey – TNS Poland, 2015).

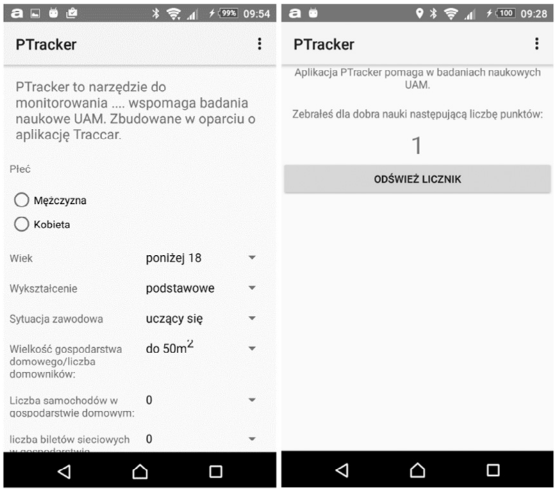

Fig. 1. Entrance questionnaire and the user's panel in the application.

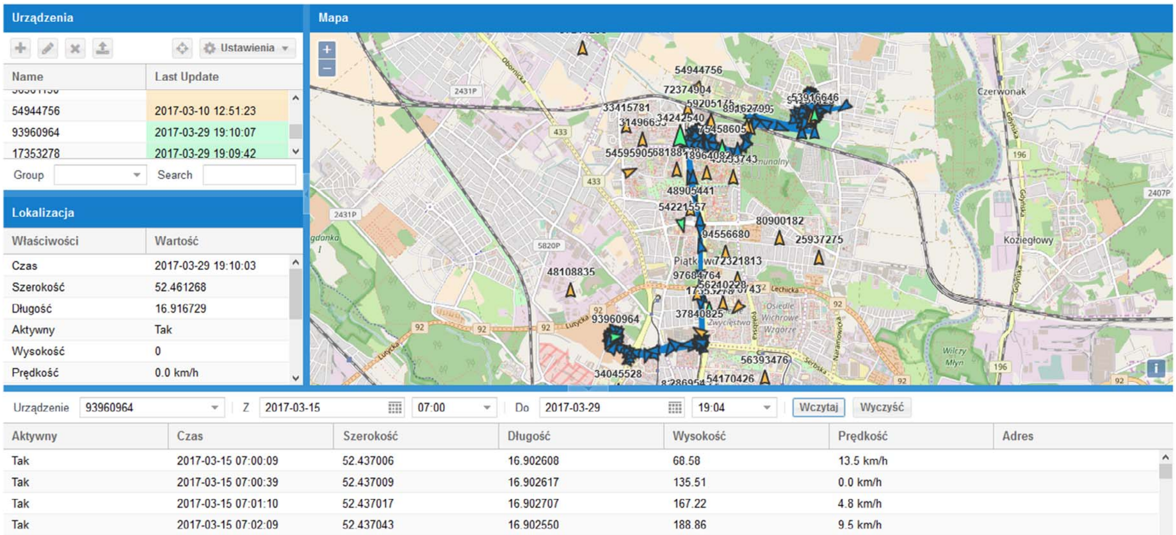

Fig. 2. Control panel (web-based map service).

There was also substantive reason for this choice. Students are a group which is often underrepresented in traditional transport surveys. This was the case also in Poznań – a city selected as the research area. In 2013, the Complex Mobility Survey (CMS) was conducted in the city and the emphasis was on permanent and officially registered residents. At the same time students (who are often registered in their parents' location and tend to be renters – in some cases without official contracts) were included and taken into account only in a smaller part of the analyses conducted in the CMS. It should be underlined that students are a huge group of city users (see Gadziński and Radzimski, 2016). According to the Statistical Office in Poznań, in 2015 the total number of students in Poznań equalled more than 116 thousand. Taking this into consideration, the knowledge of the travel behaviour of students seems to be crucially important for local authorities. Therefore, collected data could be used in the future for public purposes.

To our survey we invited students from the greatest university campus in Poznań (Adam Mickiewicz University), located in the outskirts of the city. More than 1000 invitations were sent via e-mails to students' (and ex-students') mailboxes. Information on the survey was also distributed by the faculty's official webpages, social media, posters and visual information on the monitors in the university buildings. What is more, small prizes for ten (randomly selected) users of the application were established.

The survey was conducted between December 2016 and April 2017. Finally, 104 respondents installed the application 'TwojaTrasa' and filled in the initial questionnaire. In 16 cases the quality of data was very low (incomplete traces, a short term of using, empty databases) so we decided to exclude them from our final dataset. In the survey sample, students were dominating (74%). Most of the respondents were under 30 years old (78%) and had at least secondary education (98%). There were also a little more men (55%) than women.

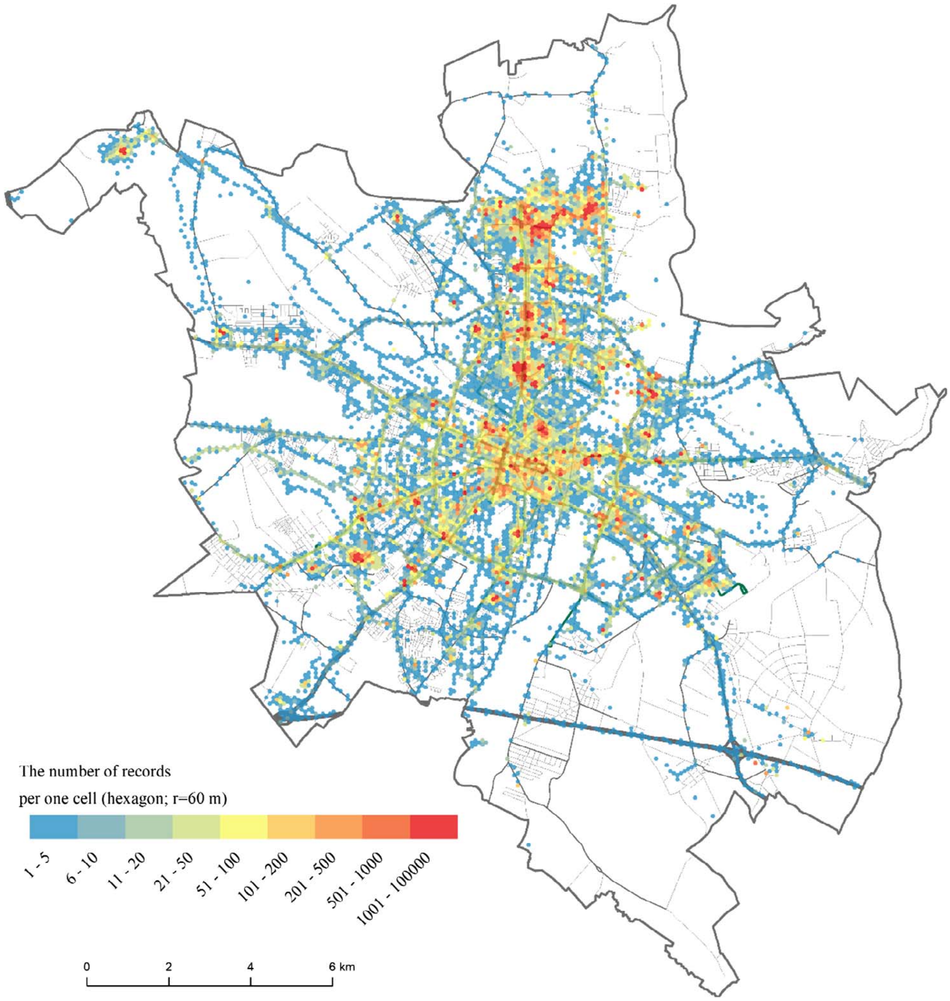

Fig. 3. Spatial distribution of collected data within the boundaries of Poznań.

3.3. Survey evaluation

In our pilot study we collected 2,923,433 data with saved location and other parameters. To prepare the databases we used commonly known and popular programs such as Excel 2016 and Statistica. The spatial distribution of collected data was presented in a Fig. 3 with the use of ArcGIS 10.3.1. It seems that gathered materials (especially the high precision of the data obtained and complete spatiotemporal trajectories which can be correlated with socio-demographic characteristics of individuals) give great analytical capabilities. However, it should also be mentioned that during our study some important problems and challenges appeared.

First of all, at the stage of the survey construction we were faced with many technological issues. The whole process was extended in time and finally lasted several months. This time was spent mainly on consultations with IT specialists, their programming work and the testing phase. Especially the last mentioned activity was very time-consuming but also necessary to avoid the problems with the functioning of the application, data transfer and so on. However, such a long time spent on the survey construction could also result from the fact that this was our initial experience with surveys on the use of smartphones. What is more, the existing literature on this topic is rather limited so we could not have learnt much from good practices. On the other hand, it seems that works on research construction as well as extensive software tests should be an important part of each study with the use of smartphones (cf. Pei et al., 2013) and this always requires adequate amount of time.

When using the application survey participants reported also some important problems during the core part of the study. Therefore, after the survey we decided to collect their experience and additionally, to identify the barriers which discouraged other persons from joining the research. For these purposes, we prepared a short on-line questionnaire. It was distributed with the use of the same channels as the earlier information on the survey (by e-mails, faculties' webpages, social media, etc.). In this way, we wanted to reach out to the same audience, i.e. the people who had already been familiar with the organised pilot study. During the two weeks of this post-survey evaluation, we collected 115 opinions, suggestions and comments. The socio-demographic structure of the sample was similar as in the pilot study with the use of smartphones (we noticed however a slightly higher share of mid-aged and working people as well as women). Most of the respondents who filled in the questionnaire were students (67%) and young adults (under 30 years old – 70%) with higher or secondary education (98%). There was almost a perfect balance between the number of women and men. Questionnaires were filled in by 30 participants of our pilot study and 85 individuals who were not involved in our research with the use of smartphones.

As the main problems occurring during the survey, participants identified a shorter battery life and the need to recharge it frequently (answer signed by 82% of users). Significantly fewer respondents indicated slower phone operation (37%). Other problems were generally not reported. Prizes were not a very strong motivation to participate in the study. 73% of the respondents answered that they could participate in such surveys also without any prizes. However, the participants of the pilot study who filled in also a post-survey questionnaire in most cases (80%) agreed that there should be some compensation for participation. Most of them were convinced (53% of respondents) that such a compensation should amount to 100–200 zlotys (25–50 Euro).

Surprisingly, the main reason for the group of respondents who did not participate in the pilot study was the lack of information about the survey (the answer was selected by 64% respondents). It could be associated with some commonly known disadvantages of disseminating information about surveys by e-mails or webpages. According to Wright (2005), an on-line advertisement is often considered an invasion of privacy, a spam, or is just ignored or missed among many similar messages. Therefore, it was quite possible that people did not read the information about the survey. The other popular explanations provided by the respondents concerned such issues as the fear for faster battery drain (14%), the desire to protect privacy (13%) or the lack of interest in the study topic (11%). For a certain group of respondents technological issues were the main obstacle. 14% of people who filled in the questionnaire (and did not participate in the pilot study) had a phone with an operating system other than Android, and 4% did not have a smartphone. The installation of the application or finding it in the app store were serious problems for further 11% of the respondents.

Among solutions and improvements encouraging participants to take part in the future surveys with the use of mobile phones, respondents most frequently mentioned the need to provide more detailed information about the survey construction and the principles of privacy protection (32%). Quite popular answers were also: "a guaranteed compensation for participation" (27%) and "a help with finding and installing an application" (24%). Applications compatible with operating systems other than Android will encourage further 20% respondents to participate in the survey. In turn, the answer "nothing" was selected only by 12% of the people who filled the post-survey questionnaire and did not participate in the pilot study before. Most of the respondents (69%) from this group claimed also that there should be a compensation for the participation in such surveys. Its value was estimated usually at 50–100 zlotys (43% of answers).

Finally, we should also mention some problems in the phase of database preparation. Processing huge amounts of data was very time-consuming and caused several computer software failures in our study. Among the raw data we found occasionally empty records, information errors and some unbelievable data. It required a lot of effort and time to remove all of these disruptions. What is more, popular statistical programs poorly supported the analyses on large data sets. Therefore, in more sophisticated analyses (including, e.g. travel mode detection) advanced statistical tool had to be used. We should also notice that even simple spatial analyses with the use of big data required rather a good knowledge of GIS.

Undoubtedly, the conducted pilot study proved that in a relatively short time large datasets could be collected. What is more, the obtained information is very precise and creates great analytical capabilities. However, there appeared also some important problems and challenges, which to some extent could overshadow these benefits. Therefore, in the next section, we focus on the potential of the data obtained from smartphones and the prospects of using them on a broader scale especially for the purpose of public policies. We divided our discussion into three parts concerning the following issues: (a) the survey construction and technological issues, (b) big data analyses, and (c) sampling.

4. Discussion – problems, limitations, challenges

4.1. Survey construction and technological issues

First of all, based on our experience, we should admit that the use of mobile phones gives great opportunities for researchers especially during the process of making a survey (cf. Lane et al., 2010). Researchers have relatively high flexibility in designing it. For example, they can decide what the level of participants' engagement should be (an active or passive logging mode) or what types of data should be downloaded to the server (see Lane et al., 2010; Jiang et al., 2013). There is still an increasing opportunity to obtain different types of data using only one smartphone application or even to combine several applications to receive the necessary data. The possibilities seem to be almost unlimited. In our pilot study we have considerable flexibility in the selection of the range of collected information and their resolution. What is more, the integrated questionnaire makes it possible to obtain basic information about the respondents without any additional effort. With the same app, we could organize similar research almost anywhere, because the direct contact with a respondent is not necessary.

However, we should also indicate some problems with a broader use of smartphones in travel behaviour surveys. The potential barrier could be the fact that obtaining data with smartphones seems more problematic than in the cases of cell-tower-based data (usually obtained directly from mobile operators) or GPS devices. They usually require a dedicated IT system and an application gathering the location data (therefore the collaboration with IT professionals seems to be essential and so it was in our pilot study), which could significantly increase the cost of research. Moreover, users could use different operation systems, which is another challenge for researchers, some of whom share such doubts. Yue et al. (2014, p. 72) claim that the surveys with the use of A-GPS data from smartphones “beside great advantages, have also disadvantages in terms of the cost, efficiency, penetration rate, and resolution in spatial, temporal, and longitudinal dimensions”. However, we should honestly admit that these issues concerned also traditional surveys based on travel diaries and paper-and-pencil questionnaires or GPS devices. In most cases, they are rather expensive and obtained information could be incomplete or inaccurate (Shen and Stopher, 2014). For example, the total costs of the Complex Mobility Survey[2] conducted in the Poznań Metropolitan Area with traditional methods amounted to around 0.5 million Euro. At the same time, the cost of our pilot study did not even reach 1% of this sum. As expected, in our survey the sample was much smaller, but we should also notice that most of our costs were allocated to the IT system and mobile application and even a substantial increase in the number of survey participants should cause only a small growth in expanses. Zhao et al. (2015) presented a similar conclusion. In their field tests with the use of smartphones (conducted in Singapore together with the Household Interview Travel Survey) they admitted that the cost of collecting additional days of data was minimal and decreased over time. Additionally, created tools could be used also in the future research.

Furthermore, all the costs, efficiency and resolution seem to become less and less important together with technology development. Smartphones are increasingly widespread in the society so there is still no need to buy GPS devices for survey purposes. A-GPS data have better resolution than raw GPS data from mobile phones used in the first travel surveys (eg. Ohmori et al., 2005). Only the problem with the energy efficiency still seems to be crucially important. In our pilot study, most of the participants (who filled in the post-survey questionnaire) confirmed that a rapid battery drain was a serious problem. What is more, also a significant group of potential application users resigned from the participation in the survey because of an expected need for frequent battery recharging. Zhao et al. (2015) admit that battery consumption is a key aspect of reducing user burden in surveys with smartphones.

We should also notice that the resolution of obtained data in such surveys is generally associated with the level of energy consumption and it depends on the decision of a researcher to some extent. When he/she strives to obtain very detailed locational data, these data should be saved in short time intervals, which also results in faster battery drain. Therefore, the resolution should be appropriately selected for the needs of a particular survey (to minimize the energy consumption and commitment required from the participants because of the need to recharge a battery frequently). There are also some attempts to optimize the relation between resolution and efficiency. Geurs et al. (2015) programmed their application to minimize the number of saved data when the participant of the survey is stationary (staying at home or at the office) and to maximize when he starts to move. Such solutions and new, more powerful batteries seem to resolve this important technological issue in the nearest future.

4.2. Big data analysis

One of the most serious challenges for the popularization of the transport research with the use of smartphones could be a huge amount of data obtained from such surveys. This can cause problems for an easy and fast use of these data for public purposes. In our pilot study, we collected more than 3 billion of records with the information about the location, speed, altitude, time, user’s ID and battery level. Additionally, we received also answers from initial questionnaires from above 100 application users. In other studies, databases with even more records were reported (see Geurs et al., 2015; Zhao et al., 2015).

Our analyses showed also that such a huge amount of data requires a great engagement of researcher. For example, he/she needs to check the quality of obtained information, remove incomplete or suspicious records and prepare the final databases. All these tasks can be very tedious and time-consuming. What is more, it could also be difficult to analyse or reduce these data to obtain some necessary information. Of course these processes can be automated to some extent, but it will undoubtedly increase the complexity or/and cost of the whole survey. It is worth noticing that there is a rich body of literature concerning the challenges of big data analyses. Many authors focus on statistical issues resulting from the massive sample size and high dimensionality (Wu et al., 2014; Fan et al., 2015). The other important problem can be the fact that some applications have strict limits on the size of the data they can handle (Jacobs, 2009). Naturally, there are also hardware limitations. In this matter Gu et al. (2016, p. 157) mention such issues as less-than-ideal computer power, no cache coherence, a small amount of fast memory, and restrictive synchronization primitives. It seems that all these issues connected with big data analyses can be an important barrier also in the popularization of surveys with the use of smartphones. In this context we could agree with Jacobs (2009, p. 39) who formulated “the big truth about big data in traditional databases: it’s easier to get the data in than out”.

We should also notice that in the studies with the use of smartphones some types of data on travel behaviour are difficult to obtain. Personal motivation, attitudes and feelings associated with travelling can be collected only with the use of additional questionnaires, but this requires greater engagement from participants. In addition, in raw location data, we do not find information about trip purposes and travel modes. Therefore, in some studies, additional data are collected with the use of questionnaires (integrated with the mobile app, web-based or traditional) or some additional functionalities in the app (e.g. Vlassenroot et al., 2015). Such solutions, however, increase the level of the commitment of survey participants. There is a risk that this could discourage some individuals from participating in the study. Thus, a researcher should be prepared to find a compromise between the range of data and the effort put in by survey participants.

As we mentioned above, without additional survey components (e.g. questionnaires) we do not know almost anything about such important issues as travel modes or the trip purposes of participants. Of course, in the literature we can find examples of studies on the automatic identification of travel modes from passively collected GPS data (Nitsche et al., 2014; Nour et al., 2016; Dabiri and Heaslip, 2018). In addition, a trip purpose identification from GPS traces is possible (Montini et al., 2014). However, in most cases

[2] Based on traditional paper-and-pencil questionnaires.

proposed methods are based on advanced algorithms or specialized computer programs. What is more, the level of the proper detection of a travel mode or a trip purpose is not perfect and reaches at most 90% (Gong et al., 2014). Therefore, the application of such methods could be problematic in surveys carried out for the needs of public sector.

4.3. Sampling and privacy

One of the most important issues, which is very often indicated in relation to a mobile data collection is the problem with the size, selection and representativeness of a sample (Wang et al., in press). This is due to the fact that smartphones appeared relatively recently and are still treated in some regions and by some social groups as a luxury good. This situation, however, is changing very rapidly. According to Global Mobile Market Report (2017), in 2017 almost 2.4 billion people will use a smartphone worldwide and in 2018 it will reach a third of the global population. Global annual growth is forecasted at 10%. The penetration rate in the developed countries in the last years significantly exceeds 60% and there are still dynamic upward trends.

The problem is that smartphone ownership is not evenly distributed in the society. This is confirmed by statistics from different countries. For example, according to the data of the Pew Research Centre in 2016 in the United States, there is a significant variation in smartphone ownership in the population depending on the age, household income and educational attainment. The highest percent of smartphone users (around 90%) was among young and mid-aged groups, well-educated persons (college graduates) and people with the highest material status. In the older age group (65+) only 42% of people had a smartphone. Similar results were reported also in other surveys (TNS Poland, 2015; ACMA, 2013, 2015). Therefore, one of the most important challenges which appears in the studies with the use of smartphones is to obtain the appropriate number and structure of participants. This problem was solved only in very few studies where the smartphones were used. In the Dutch Mobile Mobility Panel (see Geurs et al., 2015) due to sampling, a group of survey participants were equipped with smartphones for the research period. Due to that fact, they obtained representative results for all age groups. Another popular solution is to restrict the study to a specific social group. There are several studies with the use of smartphones where the sample was limited only to students (Mohd Suki, 2013; Park and Lee, 2012) or to young adults (Taylor et al., 2011; Fan et al., 2012). We also applied a similar approach in our pilot study (by directing it mainly to students).

There appears also another problem connected with a smartphone as a research tool. According to reports from different countries (ACMA, 2013, 2015; Pew Research Centre, 2015; Android in Poland, 2015), a significant group of people uses only the basic functionalities of their mobile phones (phone calls, text messages). At the same time, such activities as downloading and installing apps are common only in younger age groups. Therefore, we can assume that some users may have a problem with the participation in travel surveys with the use of smartphones due to their technical skills (e.g. they do not know how to download an application or are afraid of doing this). A similar conclusion can also be drawn from our pilot study. During the phase of data collection we received 14 questions (via e-mail) concerning technological issues. Most of them were related to the problem with finding an app in an app store. In three cases some technological issues with turning the app on (this was probably because of too old version of the Android system installed in a smartphone) also appeared. According to the opinions gathered during the post-survey evaluation, a significant number of respondents (around 11%, mainly mid-aged) resigned from the participation in our pilot study, because they were not able to find and/or install the application. Consequently, the help in this matter offered by the organizers was one of the most important factors which could encourage people to participate in such studies in the future. It seems, therefore, that the solution is to train such participants (individually or during group meetings – see Geurs et al., 2015), but this could cause problems with a further increase in costs, the need to encourage people to participate in the training, etc. Moreover, one of the greatest advantages of surveys with the use of smartphones is lost – the minimization of efforts in the recruitment of respondents.

Another problem reported in the literature (Wang et al., in press) is that respondents could for some reasons change their behaviour during the study period. The scale of this issue is really hard to estimate. Current studies comparing traditional travel surveys with the research with the use of smartphones (Montini et al., 2015) do not answer this question. Therefore, it seems that a great attention should be paid to privacy concerns to ensure participants that their private data are safe (Cottrill, 2014). According to Lane et al. (2010), respecting the privacy of a user is the most fundamental responsibility of a phone sensing system. In our pilot study we decided to collect only randomly assigned ID numbers of participants (a phone number entry was voluntary), so there was a limited possibility to connect the respondent identity with his or her daily track. Furthermore, we prepared a detailed privacy policy document with the information how the data will be utilized. During our survey we had only two inquires (sent by e-mails) with the questions about the private data safety. However, the post-survey evaluation showed that privacy concerns were rather an important issue for a significant part of the respondents. Moreover, several people resigned from participating in the research to protect their privacy.

Finally, we should also notice one of the greatest advantages of using smartphones in travel surveys, which can at least partially compensate for the mentioned problems with samplings. Most researchers (Greaves et al., 2010; Stopher et al., 2008) agree that due to the increased accuracy of the collected data, sample sizes of travel surveys can be significantly reduced.

5. Conclusions

Undoubtedly, the use of data obtained with smartphones might broaden the analytical possibilities in transport studies. We could find several examples of surveys in which interesting results have been provided. Also findings from our pilot study showed that even with the use of simple statistical programs, standard computers and modest budget some promising data could be collected. The great advantage of data obtained from smartphones is the fact that they could eliminate many problems that traditional self-reported surveys face. Zhao et al. (2015) list among them such issues as under-reporting of short trips, reporting inaccurate locations and times, and reporting on a “typical” day rather than the actual day. We should also underline the great flexibility in designing the survey what could be very useful for researchers.

However, based on literature review and our pilot study we were able to indicate some remarks on the utility of surveys with smartphones in travel behaviour studies. First of all, the collection of A-GPS data could be much more problematic than in the case of cell-tower-based data (usually obtained directly from mobile operators) or data obtained with GPS devices. Usually this process requires a dedicated IT system and an application gathering location data (so collaboration with IT professionals seems to be essential) what could significantly increase the cost of research. In addition, the need for a great financial investment seems to be the main barrier in the popularisation of surveys with the use of smartphones. Some rewards for participants should be considered when planning a survey budget (especially to compensate for the inconvenience of faster battery drain). Furthermore, the authors could meet sampling problems – due to the uneven distribution of mobile phones in the society. Therefore, some groups of survey participants have to be equipped with smartphones for the research period. Finally, we should also notice that the data processing is usually very complicated. Some analyses require advanced and sophisticated algorithms necessary e.g. for travel mode detection. Raw data have also many disruptions, so they should be cleaned before processing.

Due to these problems, the perspectives of a broader use of data obtained with smartphones in transport policies seem rather unclear. Generally we could find two main opinions in this matter. Some authors admit that such surveys may never entirely replace surveys that require active interaction with study participants (Vij and Shankari, 2015). Geurs et al. (2015) treat the use of smartphones also rather as the supplement to traditional research. In turn, Gong et al. (2014) claim that surveys with smartphones could become the main method used in travel behaviour studies. Lane et al. (2010, s. 149) also believe that in the nearest future “mobile phone sensing systems will ultimately provide both micro- and macroscopic views of cities, communities, and individuals, and help improve how society functions as a whole”. From our perspective this could become a reality but rather in a distant perspective. Before this happens, all mentioned barriers should be overcome. However, regardless of these doubts, we must undoubtedly agree with He et al. (in press, p. 2) that “we are fortunate to be working in exciting times, with great opportunities being provided by our new datasets”.

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