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Smartphone-based Travel Surveys: A Review

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ABSTRACT:

Interest continues to grow in the use of smartphones for travel survey purposes. Their locational and interactive potential combined with their ubiquity and pragmatism as something people are likely to keep with them and charged, makes them particularly appealing. However, several challenges remain, particularly around battery life, user acceptance as an instrument for tracking mobility and a fundamental lack of concordance on how travel survey apps should be designed. The current paper provides a review of smartphone-based travel survey apps focusing on issues around functionality, participant burden, processing requirements, data quality and costs. We identify a typology of smartphone apps, that all passively collect route information but vary in the level of automation and user interaction required. All of the apps reviewed report reasonable levels of participant satisfaction irrespective of the levels of automation and user-app interaction required. However, the accuracy with which information is accurately inferred appears to vary markedly, largely a function of the quality of data collected, which in turn is heavily influenced by the make/model of phone, and the processing algorithms employed. One common issue is battery drain, which continues to be an issue for both highly automated apps and those requiring significant user interaction. Looking forward, while the intuitive appeal of smartphones will continue to grow, we argue that developments have been constrained by attempts to integrate existing survey approaches within a smartphone environment. More attention needs to be given to the design of apps that engage users to start and finish the survey, focusing on 'smart' use of the sensors and processing routines to minimise battery consumption and on providing additional benefits for users.

KEYWORDS: ***Smartphones, travel surveys, data collection***

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1. Introduction

The proliferation of smartphones and associated apps with a locational bent to them makes them intuitively appealing for addressing many of the challenges associated with collecting personal travel data such as participation/recruitment, accuracy/quality of data, and resource requirements. Additionally, the interactive nature of smartphones, opens up new possibilities for designing surveys that focus more on the 'why' questions around travel and (potentially) facilitating behaviour change. Despite this, with some notable exceptions, smartphones remain largely at the fringes of mainstream travel survey data collection. This appears to reflect both inertia in how surveys are currently conducted and the fact we have not overcome the main challenges to the use of smartphones for collecting travel survey information on a large scale.

The current paper provides an assessment of smartphone applications in collecting travel survey information. In conducting the assessment, we initially identify why and how smartphones have been used in travel survey applications drawing from recently-published studies. We then compare/contrast smartphone capabilities against currently-used approaches including recall-based (paper and web form) and GPS surveys across key criteria of the survey including participant issues, data collection and processing, data quality, and resource requirements. Finally, we consider future possibilities opened up by smartphones to not only enhance elements of conventional surveys but to facilitate new approaches to the conduct of surveys.

2. Use of Smartphones in Travel Behaviour Studies

2.1. Rationale for Using Smartphones

First developed in the late 1990s, smartphones combine the features of a mobile/cellular telephone with a personal computer. Since their initial development, many players have entered this lucrative consumer market, with thousands of makes/models available running various operating systems now available. By 2014, there were more than 18,500 different devices running Android alone (OpenSignal, 2014). Particularly in the last 5 years, the power and versatility of smartphones has increased dramatically and their ability to be used literally anywhere has been fuelled by high-speed mobile broadband networks such as 4G. Worldwide, 1 in 8 people now own a smartphone with exponential growth in both the developed and developing world. In Australia, 79% of people now own a smartphone, up from 35% in 2010, which is a high level of ownership as Figure 1 suggests (Deloitte, 2015; Nielsen, 2012).

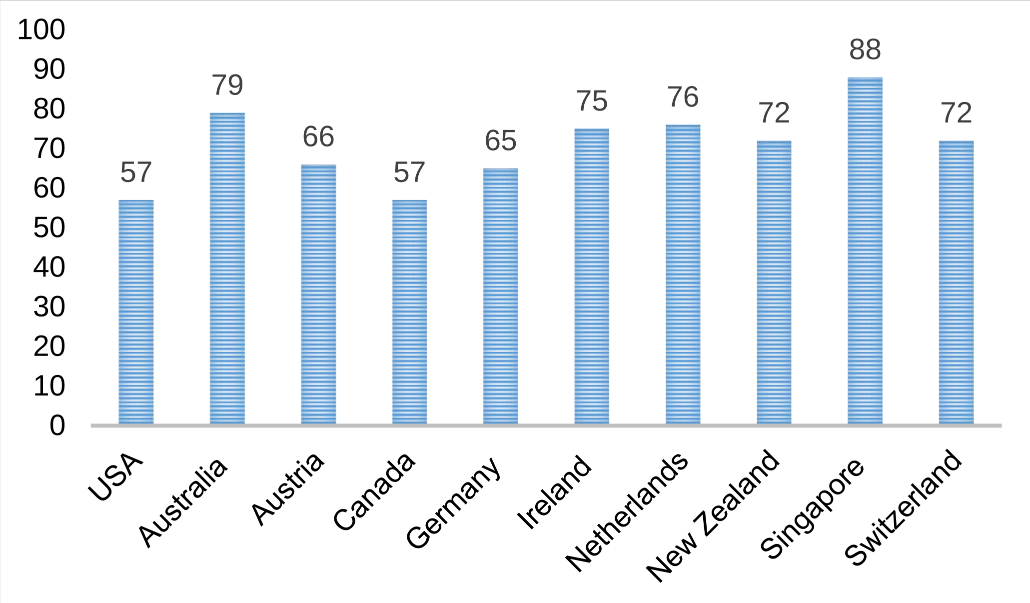

Figure 1: Smartphone Ownership by selected countries (in %)
Source: 2015 Google Consumer Barometer, 2015 Deloitte Mobile Consumer Survey for Australia

Smartphones include various technological and pragmatic/user friendly features, which have contributed to their appeal for collecting personal travel data. We argue here that they present a natural evolution of personal Global Positioning System (GPS) devices, which have been popular (although by no means ubiquitously so) in travel surveys over the last 15 years (Bricka et al. 2009). They contain several sensors (GPS, Wi-Fi, mobile network location, Bluetooth) from which positional data can be unobtrusively collected over time and space. These data in turn can be processed into useful trip information (origin, destination and route) without the need for extensive participant involvement. Additionally, the motor sensing capabilities of smartphones, through the integration of accelerometers, has facilitated the potential to detect the mode used in completing the trip (Fan et al. 2012, Jariyasunant 2014). Indeed, both Android and iOS contain development libraries that incorporate algorithms for detecting mode using the smartphone’s sensors that is available to app developers and (potentially) requires minimal adjustments. While these aforementioned capabilities have been available in purpose-built GPS devices for several years now, smartphones also provide the potential for direct integration with the survey instrument itself. In particular, the development of self-contained apps have revolutionised the potential to collect a wealth of personal information, which intuitively extends to personal travel data. Pragmatically, smartphones encompass similar traits to personal GPS devices in that they are portable, lightweight and easily carried on all modes of transport. However, unlike personal GPS devices, given their multipurpose function as a mobile telephone/computer, they are generally something people have additional motivation to keep with them and charged.

2.2. Typology of Smartphone-based Travel Surveys

The number of travel behaviour studies employing smartphone capabilities has grown significantly in the past five years with many published and unpublished/ongoing studies. As noted by Bhat (2015), as most of these studies are done independently, collective information around their design, dissemination and results is limited. For the purposes of this review, we have chosen to focus on the published literature in the last 5 years, which resulted in 14 recently conducted smartphone-based travel surveys (see Appendix A). These surveys have been developed and tested in in various countries with relatively high smartphone ownership in North America, Europe and Australasia. All the surveys share the common characteristic that a customised application has been built around a specific purpose with little evidence of an app that could be more widely-used without additional developmental work. However, there are common features underlying their design, which we use to identify a 'typology' of smartphone-based surveys, summarised in Table 2. This topology classifies smartphone apps into different categories based primarily on the functionality provided and the primary purpose of the app. The following sections describe each of these categories discussing the key functionality with illustrative examples for each.

2.2.1. Memory jogger/ trip logger

The most straightforward use of a smartphone app is to take advantage of the various positional and movement sensors to record position - in essence this is doing what a personal GPS device was designed for using the participant's own phone. The additional advantage of using the smartphone for this purpose is that the trace can be used to provide a playback for participants when completing their diary, assisting with recall. Such an approach was used in the Sydney Travel and Health Survey (Greaves et al. 2015) in which participants were recruited to complete a 7-day online travel diary with an optional smartphone app that recorded their travel. Participants repeated the study three times over three years. Overall, 45 percent of participants downloaded the app in the first wave of data collection with 66 percent taking it in Year 3, reflecting (arguably) the growing familiarity with smartphone apps during this period. Participants using the smartphone-based app reported a higher number of trips than those who did not take the app, suggesting that recall was improved (Greaves et al., 2015). The 7-day travel survey had 641 participants of which 90% are willing to complete the survey again in 12 months. This suggest that the low-level of automation using this type of survey instrument does not necessarily negatively impact user approval of the app and the web-based interface.

2.2.2. Refinement of automated data collection

Smartphone-based travel survey apps that fall under this category are primarily used to develop and refine procedures and algorithms used for automated (or passive) data collection. Building on the core functionality provided by the memory jogger/trip logger apps, these apps can also be used as a prompted-recall tool rather than a self-contained travel survey app but also contain additional processing and user correction functionality.

The *automated travel data collector* app (Abdulazim et al. 2013), tests the accuracy of the app's ability to detect the start/end of a trip (origin and destination), mode (walk, bike, car, bus, subway, street car, and train), and the purpose of the trip. To do this, a separate app was developed that respondents could use to manually report trip information, including the date and time, activity duration, and the mode used in completing the trip. The respondents' annotated data, through the application of machine learning techniques, was also used to further enhance the automated detection capabilities of the automated travel data collector. The CITYing (Shin et al. 2015) and NEMO phone (Nitsche et al. 2014) apps build on this by including the trip correction/annotation functionality within the same app. Both the CITYing and NEMO phone apps passively collect route and mode information but require users to verify the mode that they used for each trip. The accuracy of the mode detection algorithms implemented in the apps varied with the automated travel data collector having the highest reported mode detection accuracy of 98.85% in identifying six modes of travel correctly and both CITYing app and NEMO phone having a stated accuracy of approximately 80 percent. Although these apps provide some initial evidence that a smartphone is capable of providing an integrated data collection and participant interaction platform, all are currently in pre-testing and have not yet been deployed on a large-scale (with the exception of the CITYing app). Nitsche et al. (2014) argues that the scalability of the NEMO phone is possible if it is used as a supplement to traditional surveys, essentially mirroring the experience of the Sydney Travel and Health Survey (Greaves et al. 2015).

2.2.3. Supplement to a household travel survey

Household travel surveys have previously largely used more traditional survey methods with only a handful of examples of household travel surveys incorporating GPS (and with many still relying on paper diaries and interviewers). However, a handful of smartphone apps have been developed to be used as a supplement to, but not a replacement of, traditional household travel surveys. These apps have largely used the same approach as the memory jogger and passive collection with annotation functionality apps that have been discussed in previous sections, but have been run in parallel to the existing household travel surveys.

Two of the more prominent examples of these are the Future Mobility Survey (FMS) developed by Zhao et al. (2015) and the Move Smarter app (Geurs et al. 2015). Both of these studies use a web-based interface for data validation and collection of supplemental trip data in addition to the smartphone app. The FMS was deployed along with the Singapore Household Interview Travel Survey (HITS) over 2012/13 and was used by 793 participants with 22,170 user days recorded through the smartphone app and 7,856 trips validated in the web-based interface. Although the app collects the route, mode, and purpose information passively through detection algorithms, the researchers tested a custom version of the app that allowed users to annotate their trips. Results of these annotations were then compared to the automatic detection system developed by the researchers. The study found that the FMS stop detection algorithm has a detection accuracy of 95.5%. Both the FMS and MoveSmarter apps provide additional evidence of the scalability of smartphone-based travel surveys in which participants (largely) use their own devices and the apps are able to provide (seemingly) accurate data.

In testing the Move Smarter app, Geurs et al. (2015) enlisted participants from the Dutch Mobile Mobility Panel, which constitutes a representative sample of the Dutch population. 655 participants tested the Move Smarter app over 2 weeks, with 95 participants dropping out. Of these, 50 participants cited problems with the app as the reason for dropping out. This suggests a reasonably high level of user-acceptance although it should be noted that 59% of participants used a smartphone provided by the researchers. The study also found that individuals who were provided a smartphone forgot the smartphone compared to those using their own devices mirroring what has been found with GPS devices (Greaves et al., 2015). The trips recorded by the app were then validated in the web-based interface that showed the Move Smarter app had a detection rate of 20 to 25 percent.

2.2.4. Full feature testing

Much of the work that has been done using smartphones has focused on testing the capabilities of smartphones and their feasibility for travel surveys. In some ways these studies provide the most insight into both the potential challenges and benefits of using smartphones for collecting travel survey data.

The SmartMo app (Berger and Platzer 2015) has relatively less automation than other smartphone-based travel surveys, yet almost all (96%) of participants were satisfied with its ease of use. This suggests that smartphone-based apps may not necessarily have to be highly automated to increase user satisfaction in a multi-day survey although clearly this needs to be verified with further investigations. This app was used to collect route information automatically and allow participants to manually report the mode and purpose of their trips. The multi-day field test of the SmartMo app in Austria had 97 participants, half of whom reported becoming more aware of their travel behavior after completing the survey. This conclusion was supported by the Connect app (Vlassenroot et al. 2015). In an earlier version of the app called Move, the app-based participants were given the choice to either use a version that was fully automated or a version that required active trip logging. Vlassenroot et al. (2015) concluded that although passive data collection is user friendly, it fails to record some data and therefore some level of participant verification is still necessary. They also suggest that future smartphone-based travel surveys will adopt a hybrid data collection process incorporating some passive data collection but with some requirement for participants to interact with the app in some way. Another app, Peacox (Montini et al. 2015), was tested against GPS devices. The study concluded that GPS was more reliable than the app in continuously tracking trips as the battery did not drain as quickly with a dedicated device. This is unsurprising because although a GPS requires more power than alternative sensors available on smartphones, a dedicated device can be set to conserve power without regard to other uses of the device.

2.2.5. Persuasive technology

Smartphones offer the potential for greater interaction with participants rather than merely providing a passive data collection method or a more technologically advanced travel diary. This includes both travel surveys that prompt participants when key events occur as well as surveys designed to evaluate the effects of interventions.

Apps in this category provide a variety of functionality that ranges from providing a summary of the trips made by the participants by variables including the time spent travelling, the calories burnt as a result of using a specific mode of transport, as well as the monetary and environmental cost of the trip. These apps may also contain other forms of feedback including those based on the activities of other participants.

One example, the UbiActive app (Fan et al. 2012) contains supplementary questions that look into the overall physical and mental well-being of the users while completing a trip activity. The app also includes questions related to the users' happiness and satisfaction level in addition to the standard trip details. Despite UbiActive's requirement for constant user interaction, 13 out of the 17 respondents who were recruited from the University of Minnesota were satisfied with the 3-week survey experience. Similarly, the Iowa trip analyzer (Li et al. 2011) passively collected the route information and automatically detected the mode and trip purpose of 70 users. After the collection of users' trip data, a summary of the carbon footprint for the trips is transmitted via the app. Unlike UbiActive and the Iowa Trip Analyzer, which confines data collection within the app itself, the Quantified Traveler or QT (Jariyusanant et al. 2014) combines the use of the smartphone with a complementary web interface to collect travel data and to display the trip summary.

2.3. Summary

Although the apps and associated studies discussed here provide a variety of functionality and each have a specific purpose, together they provide some initial insights into the potential uses of smartphones for collecting travel survey data, either as a complement to or a replacement for other survey methods. Broadly, the studies have shown that collecting basic trip information through a smartphone device (primarily passively) is possible and that reasonable data can be collected. Furthermore, they suggest that even relatively simple apps that are primarily passive data collection devices provide some additional benefits to participants that seems to create an incentive for participants to be both more diligent and more aware of their travel. In particular, the evidence suggests that using a device participants are used to using (and crucially carrying) increases the rate with which participants use and accept the smartphone apps.

Table 1: Classification and description of smartphone-based travel survey apps

Typology	Application Name	Complementary Device	Data Input					User Control	Operating System
			Personal Data	Route	Mode	Purpose	Supplemental Data		
Refinement of automated data collection	Automated Travel Data Collector	a separate smartphone app for trip annotation/ validation	N/A	P	P	P	N/A	✓ via a separate app	Android
	CITYing	N/A	N/A	P	H	N/A	N/A	✓	Android
	NEMO Phone	N/A	N/A	P	H	N/A	N/A	✓	Android
Supplement to a national household travel survey	ATLAS	N/A	A	P	A	A	N/A	✓	iOS
	FMS	web for data validation and supplemental data	N/A	P	P	P	N/A, done via the web	✓ via the web	Android and iOS
	Move Smarter	web for data validation and supplemental data	N/A	P	P	P	N/A, done via the web	✓ via the web	Android and iOS
Persuasive technology	Active Lion	web to collect personal data and to conduct initial travel inquiries	N/A, done via web	A	A	A	N/A	✓	Android and iOS
	Iowa Trip Analyzer	N/A	N/A	P	P	P	N/A	X	Android and iOS
	Quantified Traveler (QT)	web, to display trip summary and validate date	N/A	P	P	P	N/A	X	Android and iOS
	Ubi Active	N/A	N/A	P	A	A	A	✓	Android
Memory jogger/ trip logger	Sydney Travel and Health Survey	web diary	N/A	P	N/A,done via the web	N/A,done via the web	N/A, done via the web	✓	Android and iOS
Full feature testing	Connect	N/A	N/A	H	H	H	N/A	✓	Android
	Peacox	separate journey planning app and prompted recall tool	N/A	P	P	P	N/A	✓	Android and iOS
	SmartMo	web for data validation and supplemental data	N/A, done via the web	P	A	A	N/A, done via the web	✓	Android and iOS

LEGEND:

N/A	Data not collected
P	Passive data collection
A	Active data collection
H	Hybrid data collection
✓	User can view, edit, and validate trip data
X	App has no user editing feature

3. Assessment of Smartphone Capabilities

While the previous section suggests that smartphones possess intuitive and practical appeal for the collection of personal travel data, how do they stack up against other approaches such as recall-based and GPS-based approaches? Recall-based approaches are still the most widely-used and involve the participant playing back what they did either via a self-completed diary (paper, web-based) or via an interview (phone, face-to-face). Recall-based approaches have increased in sophistication, largely down to carefully designed instruments and the incorporation of technology into various elements of the collection and checking components. It is also clear, they are more effective if an interviewer is employed to probe and clarify information (Bonnel, 2015). However, they cannot overcome the fundamental reliance on people to tell us what they did to the degree of specificity required (Bricka et al, 2009).

GPS-based surveys originated in the mid-1990s, largely in response to the drawbacks with recall-based approaches and technological enhancements that made it a viable option. Much has been written about GPS surveys (Shen and Stopher, 2015) and there have been numerous practical applications that have demonstrated that, in general, the quality and accuracy of data are improved with GPS than self-recall. However, despite this, their incorporation into mainstream travel surveys has been slower than original proponents indicated. For instance, the first all-GPS-based household travel survey was only conducted in 2009 (Giaimo et al, 2010). The reasons seem to be related to inertia in maintaining existing approaches (versus the fear of change), participant issues (privacy, burden), equipment issues, and processing requirements.

The assessment of the various approaches focuses around key issues common to any travel survey, namely i) participant-based issues, ii) data collection and processing, iii) data quality, and iv) resource requirements. Table 3 provides a summary assessment of each approach, indicating the main strengths and weaknesses.

Table 2: Assessment of Approaches

	Recall-based	GPS-based	Smartphone-based
Participant Issues	(-) High burden on respondent in completing the survey (-) Inconvenience from interviews (+) Low sensitivity to the use of new technology	(-) Not used on a regular basis, often forgotten at home (-) Low privacy (+) Low burden on respondents in completing the survey	(-) Access to smartphones (-) Technology adeptness of non-smartphone owners and elderly (-/+) Participants have partial to full control over their travel data, intermediate privacy (+) Low burden on respondents in completing the survey (+) Repeat participation and continuous use
Data Collection	(-) High burden in completing the survey manually (-) Real-time memory jogger is not available	(+) Low burden on respondents in completing the survey	(+) Low burden on respondents in completing the survey (+) Real-time memory jogger can be contained on the phone (-) Missed trips from respondents forgetting to bring their phones
Data Processing	(+) Straightforward and quick data input and cleaning	(-) Long process that requires tedious data cleaning and identification of collected travel data	(-) Long process that require tedious data cleaning and identification of collected travel data
Data Quality	(-) Data highly dependent on participant report	(-) Generally misses short trips (-) Dependent on the algorithms and processes used to	(-) Dependent on the algorithms and processes used to identify detected trip details

		identify detected trip details	(+) Additional data can be collected, processed, and presented in the app
Resource Requirements	(+) Requires less resources compared to other methods (+) Typically cheaper to develop, collect and process data	(-) Resource burden falls entirely on the research team which can be costly (-) Requires time and expertise to set up devices and process data	(+) Resource burden is shared by both the respondents and research team (-) Much more complex setup including development of app and other support infrastructure requiring specific expertise

(+) signifies positive assessment, (-) signifies negative assessment, (-/+) signifies neutral assessment

3.1. Participant issues

3.1.1. Recruitment

The challenges of participant recruitment are well-voiced within the travel survey literature (Stopher and Greaves. 2007). Recall-based approaches generally rely on telephone or face-to-face recruitment with increasing use of web-based approaches, including online consumer panels finding recent favour in some applications (Greaves et al., 2015). In general, similar methods have been used to recruit participants into GPS surveys. In this case, participants are recruited directly or indirectly by first asking if they will complete the recall survey and then subsequently asking them if they will take a device. What is unclear is whether the GPS device acts as an incentive or disincentive to participate and whether certain types of people are more likely to take the device.

Recruitment strategies and goals for smartphone-based travel surveys vary dependent on the purpose of the study. Those used to test and refine automated data collection (i.e. automated travel data collector, CITYing, and NEMO phone) do not prioritise the recruitment of a large and representative sample. Rather, the focus is on the recruitment of a few volunteers that could test the accuracy of the travel survey app in correctly detecting trip information prior to full deployment. By contrast, those conducted as a supplement to larger surveys use a similar process of recruitment to that for GPS surveys, with the additional criterion that participants have to own a smartphone that is capable of running the survey app, which can further limit the sample (Zhao et al., 2015).

This last point, leads to natural concern over the potential biases associated with use of personal smartphones. Evidently, while smartphone penetration rates continue to increase, there are still significant segments of the population who either do not own a suitable model or do not want to use it for this purpose. The various studies cited seem to present a consensus that there is a general skewing towards younger/middle-age groups with lower participation from elderly groups as might be expected (Safi et al. 2014). However, it is less clear whether there is a gender or income effect (Geurs et al., 2015). In Sydney Travel & Health Study, Greaves et al. (2015) were able to assess the smartphone uptake rates for each wave and found that there is a small difference in the take-up rate by age (with younger participants more likely to use it), women were more likely to use the app than men. Another potential bias arises from the duration of panel surveys. As compared to point-in-time surveys, panel surveys can pose more burden on respondents and lead to underreporting of trips and attrition over time.

3.1.2. User Acceptance

User acceptance in the context of travel surveys can be defined by participants' willingness to participate and diligence in completing a survey. In contrast, the associated concept of participant burden can be defined as the burden (or impact) on the participant in completing the survey in terms of time, effort, difficulty and other costs. Although technology provides one mechanism of potentially reducing participant burden by reducing what is required by participants, they also provide an additional factor that may either positively or negatively affect user acceptance.

Although user acceptance is important for all forms of travel survey methods, the use of smartphones and other more advanced technologies provide a particular challenge for user acceptance as it is possible various aspects of the smartphone app must be accepted for the app to be used at all. First, the technology adeptness of participants determines an individual's likelihood to participate in a technology-based travel survey. If a participant is unfamiliar with smartphones and does not already own and use one, then the challenges involved in learning how to use one may result in a participant being unwilling (or simply unable) to complete the survey or may do so to a lower standard than those for which a smartphone interface is more familiar (and by extension likely more intuitive). In contrast, those who extensively use smartphones may be more willing to complete the survey as it would be better integrated into their activities. This means smartphone- and internet-based travel surveys are more appealing towards younger and more active age groups (although the effect of this is possibly decreasing as older age groups increasingly adopt smartphones). To encourage the use of smartphones in large-scale travel surveys, support has to be provided to target groups who are not as familiar with smartphones. However, this needs to be done in a manner that still ensures participants diligence in completing the survey. The key advantage of smartphones over GPS devices and other travel survey methods is that smartphones are engrained into the daily routine of many individuals, which ensures constant interaction with these technologies. This can be used to overcome one of the problems with GPS surveys where participants frequently forget to carry the device with them (Rasmussen et al. 2015). Similarly, paper-based recall surveys require participants to use a paper based diary that can be easily forgotten or misplaced. However, their relative simplicity means they require little training to complete and as such may be more readily accepted than the relatively more complex GPS devices and smartphones.

For participants who already use a smartphone, the frequently high battery consumption of many travel survey apps has repeatedly been shown to reduce the willingness of participants to use the apps. For instance, half of Move Smarter participants were dissatisfied with the impact of using the app on their phone's battery life (Geurs et al. 2015). The UbiActive app was also found to significantly shorten the phone's battery life by 25 to 85% (Fan et al. 2012) and resulted in some participants switching off or uninstalling the app to save battery (Montini et al. 2015).

Another determinant of user acceptance is the reduction in respondent burden or the "perceived level of difficulty…that any individual associates with a survey they are being asked to do" (qtd. in Ampt 2003, p. 507). Self-administered travel diaries and manual reporting in recall-based surveys are frequently deemed unexciting and tedious meaning it becomes difficult to retain participant interest and diligence for long periods of time. Sample sizes of household travel surveys, as a result, have experienced a decline, while non-response has increased over the years (Stopher and Greaves 2007). GPS and smartphone-based surveys, as compared to recall-based surveys, have the potential to reduce the burden on respondents through the passive collection of travel data and the immediate availability of data that serves as a memory jogger but complete automation of travel data may also increase the privacy concerns of some participants. Furthermore, the requirement of many apps to both use a Smartphone app and complete a travel diary or other questions may limit how much smartphones can reduce participant burden unless care is taken to limit what is asked of participants. However, the additional flexibility of when to respond to the survey as well as possibly providing real-time information that is useful to participants may reduce counteract some of the additional burden from a more complex survey tool or more questions. These features are thought to have a positive impact on reducing non-response (Bonnel et al. 2015). A stated preference experiment of participants' preferences towards the use of a particular survey method could serve as an additional evidence of user acceptance.

Overall there is inconclusive evidence if travel behaviour studies that utilised smartphones to collect travel data have higher user acceptance rates than other methods although several studies have found the majority of the participants were interested in participating in similar surveys again (Greaves et al. 2015) with many participants continuing to use the smartphone app even after the conclusion of the survey period (Safi et al. 2014). A smartphone-based travel survey conducted in Japan also found that majority of the participants (over 50%) would choose the smartphone-based travel survey over paper-based survey and this effect is further induced with a reward (Maruyama et al. 2015). In comparison, Bayart and Bonnel (2015) conclude that participants in a French survey are less likely to participate in another online survey and engage in a GPS survey. These results provide some indication of a relatively high user acceptance of smartphones as a viable survey tool. There is, however, a gap in assessing user acceptance across technology-based surveys (i.e. online, GPS, and smartphones).

3.2 Data Collection & Processing

Recall-based surveys largely rely on the participant recounting what they did via a self-administered diary (paper, web-based) or through an interviewer who prompts them. While these approaches have increased in sophistication and particularly where well-trained interviewers are used, they are generally perceived as burdensome and error-prone. While data are logic-checked on the fly as much as possible, most of the data are post-processed in what can still involve a significant manual component. GPS-surveys initially operated under an 'active' model in which the device logged position but the participant was expected to provide the details. This proved highly burdensome. Subsequently, GPS surveys employed a more 'passive' approach where the device logged the data, which was processed into trips post-survey with participants relied on to verify/correct inferred trips. A wealth of literature abounds on the processing of GPS data, suffice to say this has become integral to the conduct of such surveys and can be a seriously under-estimated component of the data collection effort (Xiao et al., 2015).

Smartphone-based surveys have largely employed the 'active' GPS approach with the difference being that more processing happens on the phone itself. Processing of smartphone data encounters similar challenges to those from GPS devices. However there is no consensus among existing travel behaviour studies on how to define a movement and stop detection as well as on the best approach to detect and classify the mode used in each trip. The accuracy of these methods have quite a large range with some reporting a high trip mode detection accuracy (Zhao et al. 2015, Shin et al. 2015)and others with much lower accuracy. (Geurs et al. 2015). Furthermore, the availability of additional sensors on smartphones mean that although the accuracy of the data may be better there is the potential for the processing of the data to be much more complex and involve far larger amounts of data than GPS surveys. In addition, these additional sensors mean that the data collected from smartphones may not always be consistent with standard GPS devices and would mean that processing algorithms developed for GPS may not always be directly applicable to smartphone data.

One largely overlooked challenge with smartphones is that the skills and other requirements needed to develop and distribute an app capable of collecting travel data are becoming more advanced than those required to use other survey methods (particularly paper-based). In addition to requiring somebody with the skills to undertake the development, an app that is distributed using the App Stores for iOS and the equivalent for Android require that the apps be developed in a way that conforms to the requirements of Apple and Google respectively. These may mean making adjustments to the design that would have otherwise been employed.

3.3 Data Quality

A wealth of studies have attested to the benefits of GPS-based approaches over recall-based approaches (Shen and Stopher, 2015). By contrast, there has been little systematic research comparing smartphones with other approaches. Montini et al. (2015) in comparing the quality of data collected from a smartphone with a GPS device, concluded that despite the smartphones having a lower sampling frequency, the route generated was as accurate as the GPS device. However, battery drain issues were shown to be more prevalent for smartphones implying less data were collected overall. In a parallel study of diaries, GPS devices and smartphones, Ellison et al. (2015) reached similar conclusions around comparative accuracy. However, they were able to demonstrate this could be done without compromising accuracy by using the smartphone WiFi and network location sensors as opposed to the GPS sensor cutting down on battery drain. Anecdotally, they also found less missing trip data from the smartphone as opposed to the GPS device, presumably because participants had a greater motivation to keep the smartphone with them and charged.

While the technology-based approaches have been demonstrated as generally providing superior information, they are still far from perfect. Most GPS-surveys rely heavily on participants validating information, which is typically done after the data have been pre-processed and then communicated back to them in some way. Smartphones offer the appeal that this could be done on the phone itself, but this in turn requires the processing to be done sufficiently well on the phone for this to be viable. While it is a simpler and possibly interim approach, using the traces collected by a smartphone as a memory-jogger does appear to have merit in improving recall and quality of information (Greaves et al., 2015).

In this sense, smartphone-based surveys are more powerful than both recall-based and GPS surveys as it can instantaneously compress complex and aggregated multi-day data into comprehensible visualization that can be easily accessed by respondents on their phones. Smartphone-based surveys provide respondents the capability to view their travel data in real-time, access their trip history, and compare their average number of trips that they make in a day or in a week using each mode to that of other respondents. It is interesting to further explore how this feedback system impact the respondents travel behaviour.

3.4 Resource Requirements

While it is difficult for a variety of reasons to get accurate costings of travel surveys, they are generally an expensive activity. The main financial costs are associated with recruitment and the data collection itself, but there are also considerable costs associated with processing/cleaning data, which are often internalised by the sponsoring agency. Little is documented on the relative cost of the various approaches, suffice to say that it is a contentious area. In the case of recall-based surveys, there is likely to be development work associated with the diary and increasingly a programming requirement as web-based diaries become the norm. For those surveys using interviewers, this can entail often significant additional costs, particularly if done face-to-face as is the case for most large-scale travel surveys in Australia. For GPS-based surveys, while there are the additional costs associated with the technology itself, these are relatively low in comparison to the potential value-add in terms of the data itself. The main additional cost comes with the processing, which despite the development of processing algorithms, still has a heavy manual component involved with checking missing and spurious data.

For smartphone-based surveys, while the ‘cost’ of the data collection instrument itself is minimal, particularly if the participant’s own phone is used, there are additional programming requirements associated with app development for the various devices and operating systems in use. Several studies on smartphone-based travel surveys for instance are dedicated to exclusively refining the features of the smartphone survey app (Abdulazim et al. 2013, Shin et al. 2015, Nitsche et al. 2014). Moreover, the creation of the app itself may be relegated to contracted programmers as is the case in the development of the Active Lion app (Bopp et al. 2016). Programming and data management expertise is crucial in administering a successful smartphone-based travel survey that has minimal bugs and enhanced usability elements. Aside from the access to smartphones, participants of smartphone-based travel surveys generally need to subscribe to a data plan to allow the continuous collection of trip data although in some cases apps access Wi-Fi (Nitsche et al. 2014) to upload the collected travel information to a server. Smartphone apps however have very minimal impact on the participant's data consumption (Montini et al. 2015).

4. Looking ahead

Smartphones have been widely acknowledged as having the potential to dramatically shift how travel surveys are conducted. However, as has been discussed in previous sections of this paper, until now smartphones have largely been used as simply a new device with which GPS (and to a lesser degree other location data) can be collected and travel diaries completed by participants, each with varying degrees of automation. However, although these apps have largely proven a useful method with which to collect travel survey data, they have not yet been widely adopted and do not take full advantage of the capabilities of smartphones. This means that there are still some substantial improvements that can be made to existing smartphone apps.

Smartphones differ from previous methods used for collecting travel survey data both in terms of its raw computing power, but crucially also in being increasingly a part of people's everyday lives with many people relying on their smartphones for everything from making telephone calls to making financial transactions and payments. This has a number of important potential consequences for how travel survey methods can be conducted. First, as shown by previous studies (Guers et al, 2015 in particular), using a device to collect data that is habitually carried everywhere (regardless of if this is a smartphone or another future device) makes participants much less likely to forget the device and as a result the data collected are more reliable. Second, the wide variety of uses of smartphones mean that they can be used to log a variety of different sources of data, including traditional location data but also other contextual data that can be used to provide a more thorough picture of an individual's travel. Third, how people interact with smartphones means both that smartphones can be used to provide targeted, real-time information to participants in a manner that participants may be more willing to accept and be more engaged with but also that additional data can be collected from participants closer to the time trips are taken, ideally reducing levels of recall bias. Fourth, provided smartphone apps can be designed in a manner that is engaging, useful and unobtrusive to participants, smartphones could be used to collect travel survey data for much longer periods of time (possibly years). This is supported both by some of the longitudinal studies involving smartphones (Greaves et al. 2015) but also by the increasing prevalence of "life logging" apps that provide users with the ability to log many aspects of their lives (including travel) and in doing so provide users with useful information in an enjoyable and interesting way.

One recent area of interest is the use of gamification as a means of improving the willingness of participants to complete travel surveys. Gamification, defined as the "use of game elements and game-design techniques in non-game contexts to engage people and solve problems" (qtd. in Maican 2016), has been used in multiple disciplines such as health, education, and e-commerce to motivate behaviour and increase engagement in the use of an application for a specific purpose (Seaborn and Fels 2015). For instance, Fitbit watches have embedded gamified features that allow them to be used as a motivational fitness tool that allows users to track their fitness goals and engage in walking challenges against other users as well as a watch. In general, the concept of gamification incorporates visual elements, competitive mechanisms, and tactical incentives to turn otherwise mundane tasks, such as exercising and completing travel surveys, into an enjoyable activity. Travel surveys have only gone so far as providing real-time trip feedback to respondents (i.e. Iowa Trip Analyzer, Ubi Active, and Quantified Traveler being key examples) but have not incorporated the full gamification of travel surveys.

The use of smartphones as a travel survey tool can also provide the ability with which the multi-disciplinary nature of trip making can be evaluated. Smartphones would make it easier to fuse the collection of travel data with other supplemental information for the use in various fields – planning and health in particular. Existing travel survey apps such as UbiActive and Active Lions have already embedded health questions and measures within the travel survey app but additional integration may be useful for researchers as well as users. Usually surveys relating to individuals' health, community, and travel are done separately but with much interest in the relationship among these three factors, it would be useful to combine key questions gathered from each of these surveys and incorporate it into one smartphone-based travel survey.

Finally, with various socially connected location-aware smartphone apps gaining in popularity, some apps may be able to be used as a sampling frame for smartphone-based travel surveys. In particular, this means that data can be collected continuously from users who can then choose to participate in specific surveys that may involve either simply making use of the data the user is already collecting or used together with a targeted intervention or other modifications.

5. Conclusions

While smartphones have intuitive appeal for assisting with the collection of personal travel survey data, it is only really in the last 3-5 years that the technology has advanced to a state where it can be seriously considered alongside other data collection methods. What has resulted are a number of applications/studies all serving a specific purpose, but ranging markedly in their level of sophistication, automation and what is expected of participants. All of the studies reviewed in this paper report reasonable levels of participant satisfaction irrespective of the levels of automation and user-app interaction required. However, there is a clear self-selection bias here as all the studies are opt-ins and the use of apps is (perhaps unsurprisingly) skewed towards the younger/middle-aged groups away from the elderly. The accuracy with which information is accurately inferred appears to vary markedly, largely a function of the quality of data collected, which in turn is heavily influenced by the make/model of phone, and the processing algorithms employed. One common issue is battery drain, which continues to be an issue for both highly automated apps and those requiring significant user interaction.

Looking forward, a potentially sophisticated data collection 'tool' that costs survey researchers nothing, people have a vested interest in keeping with them and charged and is available globally is hard for travel survey researchers to ignore. The technology will continue to improve and it is our view that smarter processing algorithms using other phone sensors (e.g., Wifi, Network location) will obviate some of the battery challenges. To account for the potential biases that occur due to battery drainage and underrepresentation of some groups, it is vital for future smartphone-based travel survey results to be validated against that of other survey formats. Doing so will allow for the accurate calculation of weight adjustments that will improve the robustness and reliability of the collected data. Current applications have largely been focused on replicating existing ways of thinking about collecting travel data, which in some ways has constrained developments. We are beginning to see more creative thinking, but our view is that we have only scratched the surface in terms of really using smartphone capabilities to design more appealing surveys in the future.

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Appendix A: Smartphone-based Travel Surveys

Smartphone App	Travel Behaviour Study	Author	Location	Survey Period	Sample Size
Active Lions	There's an app for that: development of a smartphone app to promote active travel to a college campus	Bopp et al. 2016	USA	N/A	N/A
Advanced Travel Logging Application for Smartphones (ATLAS)	Design and implementation of a smartphone-based system for personal travel survey: Case study from New Zealand	Safi et al. 2014	New Zealand	58 days/ 5.8 days avg. participation days per participant	73
Automated Travel Data Collector	Using smartphones and sensor technologies to automate collection of travel data	Abdulazim et al. 2013	Canada	16 days to 9 months	6
CITYing	Urban sensing: using smartphones for transportation mode classification	Shin et al. 2015	Switzerland	Not provided	495
Connect	The use of smartphone applications in the collection of travel behavior data	Vlassenroot et al. 2015	Germany	8 months	23
Future Mobility Survey (FMS)	Stop detection in smartphone-based travel surveys	Zhao et al. 2015	Singapore	1 year	793
Iowa Trip Analyzer	Trip analyzer through smartphone apps	Li et al. 2011	USA	Not provided	70
MoveSmarter	Automatic trip and mode detection with MoveSmarter: first results from the Dutch Mobile Mobility Panel	Geurs et al. 2015	Netherlands	2 weeks	655
NEMO Phone	Supporting large-scale travel surveys with smartphones - A practical approach	Nitsche et al. 2014	Austria	2 months	15
Peacox	Comparison of travel diaries generated from smartphone data and dedicated GPS devices	Montini et al. 2015	Austria and Ireland	8 weeks (incentive of 150 euros after survey completion)	37
Quantified Travel (QT)	Quantified Traveler: Feedback Meets the Cloud to Change Behavior	Jariyasunant et al. 2014	USA	3 weeks (incentive of $15 per hour)	118
SmartMo	Field evaluation of the smartphone-based travel behavior data collection app "SmartMo"	Berger and Platzer 2015	Austria	1.5 months (incentive of 20 euros before survey completion)	97

Sydney travel and health survey	A web-based diary and companion smartphone app for travel/ activity surveys	Greaves et al. 2015	Australia	7 days (done every year since 2014, incentive of $50 AUD)	641
UbiActive	UbiActiveL A smartphone-based tool for trip detection and travel-related physical activity assessment	Fan et al. 2012	USA	3 weeks	23