CROWD4ROADS PROJECT

WHITEPAPER

Crowdsensing Scenarios for the Common Good

S. Delpriori and L. C. Klopfenstein

21 January 2019

European Commission

CAPSSI Collective Awareness Platforms for Sustainability & Social Innovation

This whitepaper provides an overview of mobile crowdsensing, as an extension to “participatory sensing” that tasks average citizens and volunteers to perform local knowledge gathering and sharing, in particular thanks to the use of mobile smart devices. The article describes existing examples from literature and related works, detailing how crowdsensing has already been adopted successfully in several different fields, which share the focus on the common good. Examples include existing systems aimed at the development of smart cities, life quality improvements for urban citizens, critical event management, social recommender systems, or road quality monitoring platforms, such as SmartRoadSense.

Wisdom of the Crowd

In 1785 the Marquis of Condorcet devised a simple, yet influential theorem, known as the "Jury Theorem", postulating about the relative probability of a group of people to arrive at a known "correct" decision. The assumptions can be reduced down to the following: each individual (i.e., each member of the jury) expresses an independent vote and each individual has a probability *p* of picking the correct answer. The theorem states that is *p* is greater than ½, adding more individuals increases the probability of the jury to vote correctly. That is, if each voter is more likely to vote correctly, **having more voters positively influences the final result**.

This theorem and several others that are cited by Surowecki in his seminal book "The Wisdom of Crowds" [SURO2005], hint at a **multiplier effect of human intellect** when trying to tackle problems in a group. A group of people working together in synergy appear to be much more successful in solving complex problems than one person working alone.

> *The aggregation of data or information from a group of people often results in better decisions than those made by a single individual from the group. ~ J. Surowiecki*

This intuition, which can be rebranded as "Collective Intelligence", justifies our trust in juries—thanks to the Marquis of Condorcet—but also explains complex behaviors like that of insect collectives or other animals. In general, this form of intelligence can be ascribed to any emergent behavior or apparent knowledge shown by a group, going beyond that of a single individual.

On the practical side, collective intelligence can refer to the capacity to mobilize and coördinate the expertise and creativity possessed by large groups of people, in order to solve problems or to create new knowledge.

Madness of Crowds

However, while the crowd's wisdom can be apparent at times, even more apparent is when **crowds go haywire**: markets, institutions, or entire democracies can behave in unforeseen ways, based on what seem to be common misbeliefs. The earliest study on this aspect of crowd psychology has been written by Mackay in 1841, documenting and debunking common quackeries of the age, such as alchemy, fortune-telling, magnetizers, and prophecies, but also discussing economic bubbles and themes apparently trivial as trends in beard styling [MACK1841].

Behavior of crowds can depend on how the network of connections *between* individuals looks, **how each component of the group influences each other**, ideas and behaviors spreading like a contagion in the case of negative or undesirable traits [CASE2018].

Living in a social group, with heterogeneous degrees of cohesion, people often rely on their social connections to interpret the environment they normally experiment. Thus, neighbors deeply affect both the way we look at the world as well as the way we react and adapt to phenomena [HART1998, FORS2011].

> *The state of being dependent, to some degree, on other people, as when one's outcomes, actions, thoughts, feelings, and experiences are determined in whole or part by others. ~ D. R. Forsyth*

Ubiquitous and continuous connection possibilities, the existence of closed online communities and the very structure of most influential social networks (i.e., Facebook and Instagram) have helped the spreading of misconceptions at a pace faster than ever.

Being always connected means broaden own communication capabilities but, for many people, also means to be always connected and engaged in some online "herds", where the ideas of an individual can resonate from other members of the same community and become more and more radical.

The possibility to easily pick people with identical interests and principles brings us to experience a tailored connected life. An *echo chamber* which enforces distortions and “groupthink” [BARB2015]. At the same time, the structure of social networks like Twitter and Instagram, with users acting as connection hubs, spreading their ideas and reaching millions, facilitates the “majority illusion” effect [LERM2016].

> *Men, it has been well said, think in herds; it will be seen that they go mad in herds, while they only recover their senses slowly, and one by one. ~ C. Mackay*

From a social network analysis perspective, if an individual belongs to a community which is too densely connected, his decisions will most likely suffer from “groupthink” [JANI1971]. Loose connections between members of the group and people external to the community may cause the groupthink phenomenon to strengthen, as contagion of new—and possibly conflicting—ideas from outside the clique cannot permeate.

Only a delicate balance between the bonding social capital—the number of connections between members of a group—and the bridging social capital of a group [PUTN2000]—i.e., the number of connections between different groups—allows its members to experience an open-minded society, where spreading of ideas and openness to new cultures benefit from the small-scale world structure of the network [TRAV1977].

However, *collective intelligence* has been shown to work reliably in groups of heterogeneous and (reasonably) independent individuals for **prediction or knowledge tasks**: that is, tasks that are menial in nature and not polarizing, such as forecasting results of a sports game or counting the number of beans in a container [SUNS2006].

Harnessing the wisdom of crowds

Over the past few years, the idea of crowd-powered problem solving has been a key research focus. In 2005, Surowiecki described a new phenomenon identified as *Crowd Wisdom* [SURO2005]. Surowiecki stated that diversity of opinion, independence of thinking, decentralization, and judgment aggregation are four essential qualities which make a crowd "smart": 10 people guessing the number of beans in a jar will be more precise on average than the sole guess from the smartest person in the same group, but only if they are allowed to make their guesses independently, avoiding bias introduced by "groupthink".

Few years later Malone et al. tried to redefine the well-known concept of collective intelligence [LEVY1997] from a crowd-powered problem-solving context [THOM2009]. Crowd Wisdom and Collective Intelligence share many aspects and, in particular, both focus on the advantage of group decision-making.

The term *crowdsourcing* was first introduced in 2006, in an article published in the *Wired Magazine* by Howe [HOWE2006].

> *Crowdsourcing represents the act of a company or institution taking a function once performed by employees and outsourcing it to an undefined (and generally large) network of people in the form of an open call. This can take the form of peer-production (when the job is performed collaboratively) but is also often undertaken by sole individuals. The crucial prerequisite is the use of the open call format and the large network of potential laborers. ~ J. Howe*

Here, key concepts are the initial open call and the presence of a large group of people (an online community in particular) willing to participate by performing the requested service. The Wikipedia project is iconic in this context: several thousands of contributors collaboratively create the most comprehensive encyclopedia of the world. From its definition it is apparent how crowdsourcing follows a top-down approach, where a central institution releases an "open call" and somehow supervises the workers.

The **list of crowdsourcing projects that successfully tackle complex problems is endless**. A well-known example is the OpenStreetMap project (OSM). Founded in 2004, OSM is based on a community of mappers that contribute and maintain data about roads, trails, cafés, railway stations, all over the world. Data added or edited by volunteers through free online tools, are collected in an open source, high quality, geospatial data set. The idea is to encourage the growth, development, and distribution of free geospatial data for everyone. Many other crowd-based projects use OSM data as a building block for their own applications. The crowdsourcing paradigm can be used in various contexts and in heterogeneous application fields. Ushahidi is another interesting case of how crowdsourcing can be employed to serve the public interest. Ushahidi, which means "testimony" in Swahili, is a platform that was initially developed to map reports of violence in Kenya after the post-election fallout at the beginning of 2008. the platform now evolved into a crowdsourcing mobile tool for crisis distributed management, and election monitoring (e.g., Ushahidi has been used in Barack Obama's election to manage volunteers and monitor voter suppression or voter issues on the day of the election).

Being inherently distributed, crowdsourcing approaches can be employed when the conventional infrastructure fails. Crowdsourcing is a communication platform that can be used during and after a disastrous event, even by public administrations and governments [BECK2015].

Crowdsourcing applications can be devised to be **used by common citizens and volunteers without particular skills**, just by asking to the community for help or by paying people to complete very simple and repetitive tasks. Tools like Amazon Mechanical Turk are the perfect means to coordinate group of people in order to allow them to cooperate for a common solution of a problem. *InnoCentive* is another crowdsourcing tool based on a simple idea: if a firm cannot solve a problem on its own, why not use the reach of the Internet to see if someone else can? This resulted in the establishment of the world's first Open Innovation Marketplace with a global network of more than 180,000 problem solvers. *CrowdSpring* is another instrument for taking advantage of a distributed network of people. *CrowdSpring* is a logo designer tool which leverages on a large community of designers to provide an effective, easy and affordable logo and custom graphics design service for small business. Applications like *CrowdSpring* are designed to employ communities of experts, not just common volunteers.

Just like in the Wikipedia example, crowdsourcing platforms can be effective in solving problems or developing complex ideas, but **they need to impose some sort of structure** on the network of volunteers. Researchers demonstrated that applications like these, need a coordinated community in order to be effectual. Large-scale social collaboration systems require significant coordination between contributors [KITT2009]. Moreover, the stronger are the ties inside teams and between units, the better the outcome [DEMO2014].

> *Participatory sensing tasks average citizens and companioned mobile devices to form participatory sensor networks for local knowledge gathering and sharing. ~ J. A. Burke*

In 2006, Burke et al. proposed the concept of *participatory sensing* [BURK2016]. It harnesses people proximity for local data gathering and sharing. When it was proposed, the definition of participatory sensing emphasized explicit user participation. In more recent years, with the widespread diffusion of smartphone sensing and mobile Internet techniques, the aim of crowd problem-solving systems has been broadened. In this context, those who tried to formalize the concept of Mobile Crowdsensing (MCS) [GUO2016] took inspiration from previous related concepts extending them by focusing more on crowd-powered data collection and processing.

> *Mobile Crowdsensing is an extension to the participatory sensing concept to have user participation in the whole computing lifecycle: leveraging both offline mobile sensing and online social media data; addressing the fusion of human and machine intelligence in both the sensing and computing process. ~ B. Guo*

MCS and participatory sensing differ in two main aspects: while participatory sensing only leverages data sensed from mobile devices by a physical community, MCS also exploits user-contributed data from online social network services (mainly open data from other projects); MCS usually harness both human and machine intelligence in both the sensing and computing process.

As pointed out by Carreras et al., MCS initiatives usually follow a mixed bottom-up/top-down paradigm [CARR2013]. MCS applications try to involve citizens in solving complex tasks or in sensing complex contexts (through their smartphones) in order to solve issues such as public decision-making, urban planning, and quality assessment campaigns of public services. In some cases, users can eventually submit reports about public issues, monitor the air pollution, or even help in earthquake early detection, then the central authority can act to get a particular result based on collected data.

Crowds as Sensors

To date, a great deal of MCS applications has been developed and used in real-world scenarios. Presenting a comprehensive list of all the applications known so far is far beyond the scope of this work, but briefly describing some illustrative examples could contribute to gain a better understanding of the MCS peculiarities and challenges.

MCS applications can serve as sensing and processing instrument in many different fields. Due to mobile devices' inherent mobility, they can be utilized for sensing tasks aimed to gain better awareness and understanding of urban dynamics. Acquiring knowledge in such context is of prime importance in order to foster sustainable urban development and to improve citizens' life quality in terms of comfort, safety, convenience, security, and awareness. Many researchers have focused on studying urban mobility and behavioral patterns in urban areas, using MCS tools support to get their research question answered. For instance, Noulas et al. analyzed check-in histories of a large set of location-based social network (LBSN) users and found out that, for human movement prediction purposes, rank distance played a bigger role than physical distance [NOUL2012].

Many other studies have investigated urban social structures and events starting from crowdsensed data. Crooks et al. studied the potential of Twitter as a distributed sensor system. They explored the spatial and temporal characteristics of Twitter feed activity responding to a strong earthquake, finding a way to identify impact areas where population has suffered major issues [CROO2013].

MCS for smarter cities

Large-scale data can be also collected by means of MCS platforms to analyze the actual social function of urban regions, a kind of data which is usually very difficult to obtain and that can be of primary importance concerning urban planning. For instance, Pan et al. started from the GPS log of taxi cabs to classify the social functions of urban land [PAN2013], while Karamshuk et al. tried to identify optimal placements for new retail stores [KARA2013]. Awareness of user location is the foundation of many modern and popular mobile applications, such as location search services, indoor positioning [YU2011], location-based advertising [GARY2008], and so forth.

But more useful and precise services can be enabled harnessing all the peculiar characteristics of personal mobile phones. As an example, Zheng et al. used crowdsourced user-location histories to build a map of points of interest which can be of help for people who are familiarizing with a new city [ZHEN2012]. Again, GeoLife [ZHEN2011a, ZHEN2011b] is a MCS platform able to suggest new friendship looking at similarities in user-location logs, while CrowdSense@Place [CHON2012] is a framework able to exploit advanced sensing features of smartphones to opportunistically capture images and audio clips to better categorize places the user visits.

In many cases, the development of a particular MCS platform has been **the answer to issues raised by pre-existing communities or grassroots initiatives**. Citizens and policymakers have usually strong interests in matters like environmental monitoring, public safety, and healthcare, where the participatory and mobile essence of the MCS approach provides a novel way for collaboratively monitor the issue being considered. Besides, the moving nature of these topics draws the attention of online and offline communities.

MCS for the common good

The potential of a community can be harnessed by MCS approaches to engage people and to make them participate in the data collection. It is not just a matter of the number of participants, rather someone who is moved by a topic not only will be more disposed to contribute but he or she will also be prone to provide better and more complete data [JAIM2015].

As an example, Ruge et al. described how their mobile application SoundOfTheCity [RUGE2013] allowed users to link their feelings and experiences with the measured noise level, helping in providing information essential to have a clearer understanding of the context (is the high noise level due to a party, a festival, or just a very crowded street?). This is an illustrative case of how qualitative data provided by users can enrich the quantitative data gathered through personal smart devices.

In short, to fully harness their potentialities when analyzing such contexts, MCS applications **should aim not only to collect as much data as possible but also to provide ways for users to enrich the collection** with thick data [WANG2013].

> *Thick data (for those, like me, who aren't familiar with the term) is data related to qualitative aspects of human experience and behavior, particularly when used as context for the analysis of a large data set. ~ T. Wang*

Other examples of MCS applications analyzing topics of common interest are: NoiseTube [MAIS2010] which was a system able to exploit volunteers' smartphones to collect data about environmental noise in users' daily lives and to aggregate them to obtain a fine-grained noise map; U-Air [ZHEN2013] inferred air quality data by heterogeneous crowdsensed data comparing them against information from sensing stations and traffic information; the *Great Backyard Bird Count* project (cited by Cuff et al. [CUFF2008]) used volunteers to continuously report the count of watched birds in the US.

MCS in critical events

MCS applications can also be used for assisting in disaster relief [LUDW2015], such as earthquakes and flooding [BENG2011], or in critical events like gas shortages in urban areas [NGUY2014].

Healthcare is another field where MCS is helping a lot by collecting a wealth of data for applications more and more useful for an aging society like ours. Google researchers did pioneering work in 2006 using health-related search queries to estimate illnesses distribution in US [FERG2006], while Wesolowski et al. exploited the widespread diffusion of mobile phones to analyze malaria spreading in Kenya [WESO2012].

MCS as a recommender system

Also, many mobile social recommendation services, like friend, place, or itinerary recommendations, has been enabled by the body of data collected by MCS platforms. Most of these systems shared the characteristic of combining mobile crowdsensed data and user-generated information from LBSN. In 2014 Yu et al. presented a system whose aim was to produce travel plan suggestions starting from data such as Points of Interest (POIs) features, temporal and spatial constraints and user data taken from social networks [YU2014]. Yang et al. developed SEALs [YANG2013] a fine-grained preference-aware location search framework which leverages the crowdsourced traces from Foursquare, using check-ins and extracting users' sentiment about locations.

More recently, Marakkalage et al. introduced a crowdsensing platform aimed at identifying POIs among elderly population in Singapore [HASA2017]. Their system can passively collect the location history through GPS sensors embedded in a user's smartphone and thus determine popular places among the elderly.

MCS for road users

Crowdsensed data in urban areas can be leveraged for public transportation system design, traffic forecasting, and real-time information systems, for monitoring the road network condition and so on. Location history is usually perceived as sensitive data by users who thus need to be motivated or reassured to take part in this kind of crowdsensing process employing some cooperation incentives.

Most researchers in this field choose to collect **data from user-provided mobile phone sensors, mainly from GPS, accelerometers, compass, gyroscopes**, and other related sensors already available on board of consumer-grade smartphones, while some others make use of other smart object items like GPS-tracking devices (which are often already on board of vehicles). Many applications on traffic dynamics are based on leveraging data from public transportation, buses, and taxis [WEN2008, CALA2011, LIU2009]. Among many it is worth mentioning the work of Giannotti et al. where, using location histories of numerous GPS tracking devices embedded in vehicles (usually for safety reasons), researchers have used mobility patterns to analyze if the current official district division reflects actual traffic flows, travel customs and center of attraction for drivers [GIAN2016].

SmartRoadSense [ALES2014] is a MCS application based on data sensed using personal user smartphone. The platform is a crowdsensing system used to monitor the surface status of the road network. The SmartRoadSense mobile app is able to detect and classify the road surface irregularities by means of accelerometers and send them to a cloud server. Aggregated data about road roughness is shown on an interactive online map and made available as open data [FRES2014], to be freely used by local administrations and road maintenance offices for a complete and up-to-date overview of the health of the road network.

References

[SURO2005] Surowiecki, J., *The Wisdom of Crowds*. Anchor (2005).

[HOWE2006] Howe, J., *The rise of crowdsourcing*. Wired magazine, 14(6):1–4, 2006.

[CASE2018] Case, N., The Wisdom and/or Madness of Crowds, online at https://ncase.me/crowds/, last accessed on 2019-01-17.

[MACK1841] Mackay, C., *Extraordinary Popular Delusions and the Madness of Crowds*, Richard Bentley London (1841).

[SUNS2006] Sunstein, C., *Infotopia*. Oxford University Press, 2006.

[BRAB2008] Brabham, Daren C., *Crowdsourcing as a model for problem solving: An introduction and cases*. Convergence (Sage Publications) 14, no. 1 (2008): 75-90.

[JANI1971] Janis IL. Groupthink. Psychology today. 1971 Nov 5;5(6):43-6.

[PUTN2000] Putnam RD. Bowling alone: America's declining social capital. InCulture and politics 2000 (pp. 223-234). Palgrave Macmillan, New York.

[TRAV1977] Travers J, Milgram S. An experimental study of the small world problem. InSocial Networks 1977 (pp. 179-197).

[DEMO2014] De Montjoye YA, Stopczynski A, Shmueli E, Pentland A, Lehmann S. The strength of the strongest ties in collaborative problem solving. Scientific reports. 2014 Jun 20;4:5277.

[KITT2009] Kittur A, Lee B, Kraut RE. Coordination in collective intelligence: the role of team structure and task interdependence. In Proceedings of the SIGCHI conference on human factors in computing systems 2009 Apr 4 (pp. 1495-1504). ACM.

[HART1998] Harton, H. C., Green, L. R., Jackson, C., & Latane (1998). *Demonstrating dynamic social impact: Consolidation, clustering, correlation, and (sometimes) the correct answer*. Teaching of Psychology, 25, 31-35.

[FORS2011] Forsyth DR. Group Dynamics. 2011.

[BARB2015] Barberá P, Jost JT, Nagler J, Tucker JA, Bonneau R. Tweeting from left to right: Is online political communication more than an echo chamber?. Psychological science. 2015 Oct;26(10):1531-42.

[LERM2016] Lerman K, Yan X, Wu XZ. The" majority illusion" in social networks. PloS one. 2016 Feb 17;11(2):e0147617.

[LEVY1997] Pierre Lévy. Collective intelligence. Plenum/Harper Collins New York, 1997.

[THOM2009] Thomas W Malone, Robert Laubacher, and Chrysanthos Dellarocas. Harnessing crowds: Mapping the genome of collective intelligence. 2009.

[GUO2016] Bin Guo, Chao Chen, Daqing Zhang, Zhiwen Yu, and Alvin Chin. Mobile crowd sensing and computing: when participatory sensing meets participatory social media. IEEE Communications Magazine, 54(2):131–137, 2016.

[CARR2013] I. Carreras, D. Miorandi, A. Tamilin, E. R Ssebaggala, and N. Conci. *Crowd-sensing: Why context matters*. In Pervasive Computing and Communications Workshops (PERCOM Workshops), 2013 IEEE International Conference on, p. 368–371. IEEE, 2013.

[BURK2016] Jeffrey A Burke, Deborah Estrin, Mark Hansen, Andrew Parker, Nithya Ramanathan, Sasank Reddy, and Mani B Srivastava. Participatory sensing. Center for Embedded Network Sensing, 2006.

[NOUL2012] Anastasios Noulas, Salvatore Scellato, Renaud Lambiotte,Massimiliano Pontil, and CeciliaMascolo. A tale of many cities: universal patterns in human urban mobility. PloS one, 7(5):e37027, 2012.

[CROO2013] Andrew Crooks, Arie Croitoru, Anthony Stefanidis, and Jacek Radzikowski. #earthquake: Twitter as a distributed sensor system. Transactions in GIS, 17(1):124–147, 2013.

[WANG2013] T. Wang. *Big data needs thick data*. Ethn. Matters, 13, 2013.

[BECK2015] Becker D, Bendett S. Crowdsourcing solutions for disaster response: examples and lessons for the US government. Procedia Engineering. 2015 Jan 1;107:27-33.

[PAN2013] Gang Pan, Guande Qi, Zhaohui Wu, Daqing Zhang, and Shijian Li. Land-use classification using taxi gps traces. IEEE Transactions on Intelligent Transportation Systems, 14(1):113–123, 2013.

[KARA2013] Dmytro Karamshuk, Anastasios Noulas, Salvatore Scellato, Vincenzo Nicosia, and Cecilia Mascolo. Geo-spotting: mining online location-based services for optimal retail store placement. In Proceedings of the 19th ACM SIGKDD international conference on Knowledge discovery and data mining, pages 793–801. ACM, 2013.

[GARY2008] Anargyros Garyfalos and Kevin C Almeroth. Coupons: A multilevel incentive scheme for information dissemination in mobile networks. IEEE Transactions on Mobile Computing, 7(6):792–804, 2008.

[YU2011] Zhiwen Yu, Yunji Liang, Bukan Xu, Yue Yang, and Bin Guo. Towards a smart campus with mobile social networking. In Internet of Things (iThings/CPSCom), 2011 international conference on and 4th international conference on cyber, physical and social computing, pages 162–169. IEEE, 2011.

[ZHEN2012] Vincent W Zheng, Yu Zheng, Xing Xie, and Qiang Yang. Towards mobile intelligence: Learning from gps history data for collaborative recommendation. Artificial Intelligence, 184:17–37, 2012.

[ZHEN2011a] Yu Zheng, Hao Fu, X Xie, WY Ma, and Q Li. Geolife gps trajectory dataset-user guide, 2011.

[ZHEN2011b] Yu Zheng, Lizhu Zhang, Zhengxin Ma, Xing Xie, and Wei-Ying Ma. Recommending friends and locations based on individual location history. ACM Transactions on the Web (TWEB), 5(1):5, 2011.

[CHON2012] Yohan Chon, Nicholas D Lane, Fan Li, Hojung Cha, and Feng Zhao. Automatically characterizing places with opportunistic crowdsensing using smartphones. In Proceedings of the 2012 ACM Conference on Ubiquitous Computing, pages 481–490. ACM, 2012.

[JAIM2015] Luis G Jaimes, Idalides J Vergara-Laurens, and Andrew Raij. *A survey of incentive techniques for mobile crowd sensing*. IEEE Internet of Things Journal,2(5):370–380,2015.

[RUGE2013] Lukas Ruge, Bashar Altakrouri, and Andreas Schrader. *Soundofthecity: continuous noise monitoring for a healthy city*. In Pervasive

Computing and Communications Workshops (PERCOM Workshops), 2013 IEEE International Conference on, p. 670–675. IEEE, 2013.

[MAIS2010] Nicolas Maisonneuve, Matthias Stevens, and Bartek Ochab. *Participatory noise pollution monitoring using mobile phones*. Information Policy, 15(1,2):51–71, 2010.

[ZHEN2013] Yu Zheng, Furui Liu, and Hsun-Ping Hsieh. *U-air: When urban air quality inference meets big data*. In Proceedings of the 19th ACM SIGKDD international conference on Knowledge discovery and data mining, p. 1436–1444. ACM, 2013.

[CUFF2008] Dana Cuff, Mark Hansen, and Jerry Kang. *Urban sensing: out of the woods*. Communications of the ACM, 51(3):24–33, 2008.

[LUDW2015] Thomas Ludwig, Christian Reuter, Tim Siebigteroth, and Volkmar Pipek. *Crowdmonitor: Mobile crowd sensing for assessing physical and digital activities of citizens during emergencies*. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, p. 4083–4092. ACM, 2015.

[BENG2011] Linus Bengtsson, Xin Lu, Anna Thorson, Richard Garfield, and Johan Von Schreeb. *Improved response to disasters and outbreaks by tracking population movements with mobile phone network data: a post-earthquake geospatial study in Haiti*. PLoS medicine, 8(8):e1001083, 2011.

[NGUY2014] Dong-Anh Nguyen, Tarek Abdelzaher, Steven Borbash, Xuan-Hong Dang, Raghu Ganti, Ambuj Singh, and Mudhakar Srivatsa. *On critical event observability using social networks: A disaster monitoring perspective*. In Military Communications Conference (MILCOM), 2014 IEEE, p. 1633–1638.IEEE, 2014.

[FERG2006] Neil M. Ferguson, Derek A. T. Cummings, Christophe Fraser, James C. Cajka, Philip C. Cooley, and Donald S. Burke. *Strategies for mitigating an influenza pandemic*. Nature, 442(7101):448, 2006.

[WESO2012] Amy Wesolowski, Nathan Eagle, Andrew J Tatem, David L Smith, Abdisalan M Noor, Robert W Snow, and Caroline O Buckee. *Quantifying the impact of human mobility on malaria*. Science, 338(6104):267–270, 2012.

[YU2014] Z. Yu, et al., *Recommending travel packages based on mobile crowdsourced data*. IEEE Communications Magazine, 52(8):56–62, 2014.

[YANG2013] D. Yang, et al., *Fine-grained preference-aware location search leveraging crowdsourced digital footprints from lbsns*. In Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing, p. 479–488. ACM, 2013.

[HASA2017] S. Hasala Marakkalage, et al., *Identifying points of interest for elderly in Singapore through mobile crowdsensing*. 2017.

[WEN2008] H. Wen, et al. *Operational analysis on Beijing road network during the Olympic Games*. Journal of Transportation Systems Engineering and Information Technology, 8(6):32–37, 2008.

[CALA2011] F. Calabrese, M. Colonna, P. Lovisolo, D. Parata, and C. Ratti. *Real-time urban monitoring using cell phones: A case study in Rome*. IEEE Transactions on Intelligent Transportation Systems, 12(1):141–151, 2011.

[LIU2009] Liang Liu, Assaf Biderman, and Carlo Ratti. Urban mobility landscape: Real time monitoring of urban mobility patterns. In Proceedings of the11th International Conference on Computers in Urban Planning and Urban Management, p. 1–16, 2009.

[GIAN2016] F. Giannotti, et al., Understanding human mobility with big data. In Solving Large Scale Learning Tasks. Challenges and Algorithms, p. 208–220. Springer International Publishing, 2016.

[ALES2014] G Alessandroni, L C Klopfenstein, S Delpriori, M Dromedari, G Luchetti, B Paolini, A Seraghiti, E Lattanzi, V Freschi, A Carini, et al. *Smartroadsense: Collaborative road surface condition monitoring. Proceedings of the UBICOMM*, p. 210–215, 2014.

[FRES2014] Valerio Freschi, Saverio Delpriori, Lorenz Cuno Klopfenstein, Emanuele Lattanzi, Gioele Luchetti, and Alessandro Bogliolo. *Geospatial data aggregation and reduction in vehicular sensing applications: The case of road surface monitoring*. In Connected Vehicles and Expo (ICCVE), 2014 International Conference on, p. 711–716. IEEE, 2014.

Crowd4Roads is a project that has received funding from the European Union's H2020-ICT-2015 Programme for research, technological development and demonstration under grant agreement no 687959. Please see http://www.c4rs.eu/project/ for more information.