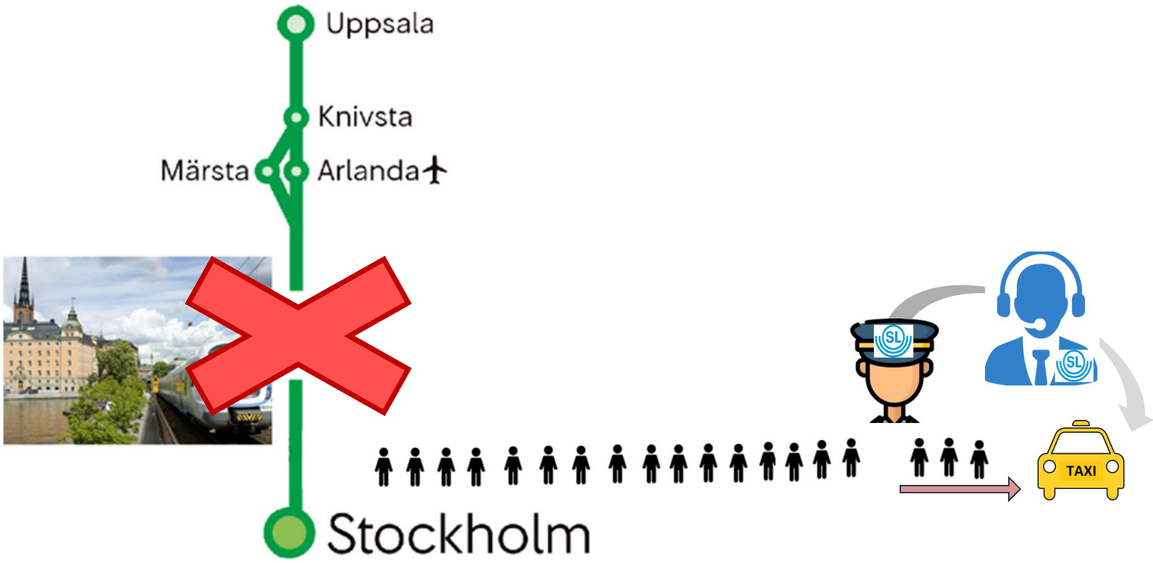
SHARP

Pre-study of Data Sharing for Demand-Responsive and Public Transport System-of-Systems

Public report



Project within Systems-of-Systems for Urban Mobility (SoSSUM)

Author Erik Jenelius and Matej Cebecauer

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Content

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1. Summary

Collaboration between demand-based and conventional fixed public transport can create a robust and predictable transport service system-of-systems (SoS). Sustainable business models in this area could help lower congestion, lower overall fossil fuel usage, decrease pollution, shorten travel times, and decrease costs of person-km, while increasing the revenue for transport providers. The purpose of this pre-study is to improve the efficiency, robustness and attractiveness of shared urban mobility by facilitating better real-time integration between fixed public transport services and demand-responsive taxi services.

The pre-study organized a stakeholder workshop, which introduced two main use cases for public transport and taxi data sharing: (1) last-mile service and (2) disruption management. Last-mile service in low-density areas is a frequently highlighted application of integrated fixed and demand-responsive services. In such areas, taxis can serve as last-mile service connecting to a mass PT line.

The second use case in disruption management. This pre-study explores the potential of a system-of-systems in which the PTA enters an agreement with one or several taxi companies to provide bridging services with taxis during PT disruptions. The purpose of the collaboration is to complement and potentially reduce the need of bridging buses, reduce the costs of reimbursements and potentially fully replace them, reduce the waiting times and the responsibilities of the individual travellers to arrange alternative modes of transport. Through real-time sharing of travel demand data the SoS framework can better utilize available taxi capacity through proactive dispatching and ride sharing. Real-world examples and simulation studies suggest that such an approach can successfully reduce traveler waiting times and environmental impacts, whereas the cost savings for the PTA need further study.

The preliminary data analysis aimed to investigate the potential of integrating available public transport and taxi data sources. To demonstrate the effects of public transport disruptions, we selected a case study involving a disruption of 23 metro stations located on the red line in Stockholm. Taxi and public transport demand data from one historical day (1st April 2016) were used. The data are used to simulate the effects of different disruption management strategies on passenger waiting times and operational costs. A strategy where the public transport authority coordinates taxi journeys leads to considerably shorter waiting times and lower costs compared to if the travelers themselves book the trips.

The stakeholder discussions, literature review and data analysis suggest that a system-of-systems involving taxi and public transport is a promising approach for public transport disruption management. Further research is needed to develop the business models of SoS for disruption management in a Swedish setting. Further work should also be directed towards a pilot study.

2. Sammanfattning på svenska

Samverkan mellan efterfrågestyrd och konventionell kollektivtrafik kan skapa ett robust och pålitligt system-av-system (SoS) för transporter. Hållbara affärsmodeller på detta område kan bidra till att minska trängseln, användningen av fossila bränslen och föroreningarna, förkorta resetiderna och minska resekostnaderna samtidigt som intäkterna för transportföretagen ökar. Syftet med denna förstudie är att förbättra effektiviteten, robustheten och attraktiviteten hos delad mobilitet i städer genom att möjliggöra bättre realtidsintegration mellan fix kollektivtrafik och efterfrågestyrda taxitjänster.

Förstudien organiserade en workshop med avnämare, som presenterade två case för datadelning mellan kollektivtrafik och taxi: (1) sistamilen-tjänster och (2) störningshantering. Sistamilen-tjänster i områden med låg befolkningstäthet är en ofta utpekad tillämpning av integrerade fixa och efterfrågestyrda tjänster. I sådana områden kan taxibilar fungera som en sistamilen-tjänst som knyter an till en stomlinje i kollektivtrafiken. I detta case subventioneras taxibolagen för att tillhandahålla tjänsten och den integrerade tjänsten ingår i PT-biljetten. Denna dörr-till-dörr-tjänst uppmuntrar människor att använda kollektivtrafik + taxi i stället för privat bil eller taxi hela vägen. Inom en plattform för delning av realtidsinformation plattform skickar kollektivtrafikoperatören i realtid fordons- och passagerarinformation till taxibolagen eller en neutralt informationscentral. Med den här informationen kan taxibolagen skicka ett lämpligt antal fordon till varje station för att hämta resenärer. Godkända turer bekräftas till kollektivtrafikoperatören eller det neutrala informationsnavet för att hålla reda på antalet betjänade resenärer.

Det andra caset är störningshantering. Järnvägssystem är känsliga för oväntade händelser som infrastrukturbrott, tekniska fel, svåra väderförhållanden och olyckor. Nuvarande praxis i Stockholm är att hantera störningar på högkapacitetslinjer genom att sätta in ersättningsbussar och erbjuda resegaranti. Ersättningsbussar är kostsamma, tar ofta lång tid att komma fram och kan inte hantera passagerarbelastningen på ett helt tunnelbane- eller pendeltåg. Resegarantin kostar också kollektivtrafikmyndigheten betydande belopp varje år. Den här förstudien undersöker potentialen i ett system-av-system där kollektivtrafikmyndigheten ingår avtal med ett eller flera taxibolag för att tillhandahålla ersättningstjänster med taxibilar vid kollektivtrafikstörningar. Syftet med samarbetet är att komplettera och eventuellt minska behovet av ersättningsbussar, minska kostnaderna för resegarantin och eventuellt helt ersätta den, minska väntetiderna och de enskilda resenärernas ansvar att ordna alternativa transportsätt. Genom att dela realtidsdata kan SoS-ramverket bättre utnyttja tillgänglig taxikapacitet genom proaktiv trafikledning och delning av fordon.

En genomgång av litteratur relaterad till affärsmodeller och systemarkitekturer för MaaS-system och strategier för avbrottshantering av kollektivtrafik har utförts. Baserat på workshopens resultat har förstudien främst inriktats på system för avbrottshantering. Exempel från praktiska lösningar och simuleringsstudier tyder på att ett sådant tillvägagångssätt framgångsrikt kan minska resenärernas väntetider och miljöpåverkan, medan kostnadsbesparingarna för kollektivtrafikmyndigheten behöver studeras ytterligare.

Dataanalysen i denna förstudie syftade till att undersöka möjligheterna att integrera tillgängliga kollektivtrafik- och taxidatakällor. För att illustrera effekterna av kollektivtrafikstörningar valde vi en fallstudie med 23 tunnelbanestationer på den röda linjen i Stockholm. Fallstudien simulerar en störning under vilken stationerna inte kan betjänas med tunnelbana. Efterfrågedata från taxi och kollektivtrafik från en verklig dag (1 april 2016) användes. Analysen visar att det är möjligt att integrera de två datakällorna. Data användes för att simulera effekterna av olika strategier för hantering av avbrott på passagerarnas väntetider och driftskostnader. En strategi där kollektivtrafikmyndigheten koordinerar taxiresor leder till avsevärt kortare väntetider och lägre kostnader jämfört med om resenärerna själva bokar resorna.

Diskussionerna med avnämare, litteraturstudierna och dataanalysen tyder på att ett system-av-system som innefattar taxi och kollektivtrafik är ett lovande tillvägagångssätt för hantering av störningar i kollektivtrafiken. Vidare forskning behövs för att utveckla affärsmodeller för störningshantering enligt SoS i en svensk kontext. Ytterligare arbete bör också riktas mot en pilotstudie.

Förstudien bidrar till FFIs övergripande mål att minska vägtrafikens miljöpåverkan. Genom att tillhandahålla lösningar för effektivare och robust hantering av kollektivtrafikstörningar bidrar förstudien till att locka fler resenärer till kollektivtrafiken, vilket kommer att bidra till att minska miljöfarliga utsläpp som CO2 och NOx. Förstudien bidrar till målen för SoSSUM genom att undersöka möjligheterna till en smart mobilitetslösning för städer, nämligen hantering av störningar i kollektivtrafiken med realtidsdata om efterfrågan, baserat på SoS-tänkandet. Den utvecklade lösningen är avsedd att öka transportsystemets effektivitet under störningar, vilket ökar systemets tillförlitlighet och robusthet.

3. Background

Large cities around the world, including Stockholm, are experiencing increasing congestion. Traffic is one of the main sources of air pollution and global warming. Apart from the private cars, today’s transport system consists of multiple sub-systems, including public transport and demand-responsive services such as taxi companies. As of yet, integration between public transport and taxi services is at a relatively rudimentary level. Large public transport hubs are typically complemented with waiting and drop-off areas for taxis, where travellers can transfer from one mode to the other. This is a type of system integration at the static infrastructural level. However, collaboration of the actors in these sub-systems can potentially significantly improve the efficiency and quality of transport, defined by FFI Strategic Initiative SoSSUM as the primary transport needs.

Collaboration between demand-based and conventional fixed public transport can create a robust and predictable transport service system-of-systems (SoS), providing a platform for mobility as a service (MaaS). Further, vehicle sharing in demand-responsive services can help utilize available capacity more efficiently and decrease the number of vehicles on the roads. Sustainable business models in this area could help lower congestion, lower overall fossil usage (decrease of vehicles), decrease pollution, shorten travel times, and decrease costs of person-km, while increasing the revenue for transport providers.

Integrated transport systems and MaaS are generating interest in many major cities. Some cities such as Singapore have included demand-responsive service in the public transport for a special fee (Ibrahim 2013). There are some recent studies of taxi, ride-sharing and public transport integration (Stiglic et al., 2017) and collaboration during disruptions (Zeng et al. 2013). Sharing of taxi trips is also getting more attention in the literature (Ma et al. 2013; Santi et al. 2014; Wang et al. 2018; Ta et al. 2018) and patent applications (Chen et al. 2014; Fowler 2016). A study in Singapore reveals a decrease of the total vehicle kilometers and an increase of about 20% more booking requests served in the same time (Wang et al. 2018). In New York City, such a system can be about 40% more effective and affordable than current taxi services (Santi et al. 2014).

Fixed high-capacity public transport services such as metro and commuter trains are efficient during normal operations but are vulnerable to disruptions. In Stockholm, metro and commuter train disruptions are handled in several ways (Figure 1). Bridging buses are called in to replace the rail-based service along the disrupted lines. These often take significant time to arrive, however, and are costly to keep stand-by. Further, travellers who can show that they would have been at least 20 minutes late when taking the best public transport alternative can get reimbursement for their travel expenses in alternative modes such as taxi or private car. Such alternative modes of transportation must be arranged by the individual travellers. The reimbursements are costly for Region Stockholm; in 2014, the public transport administration paid out a total of SEK 9.7 million. In 2018, the sum had more than tripled to SEK 29.1 million (Fritzon, C., 2019).

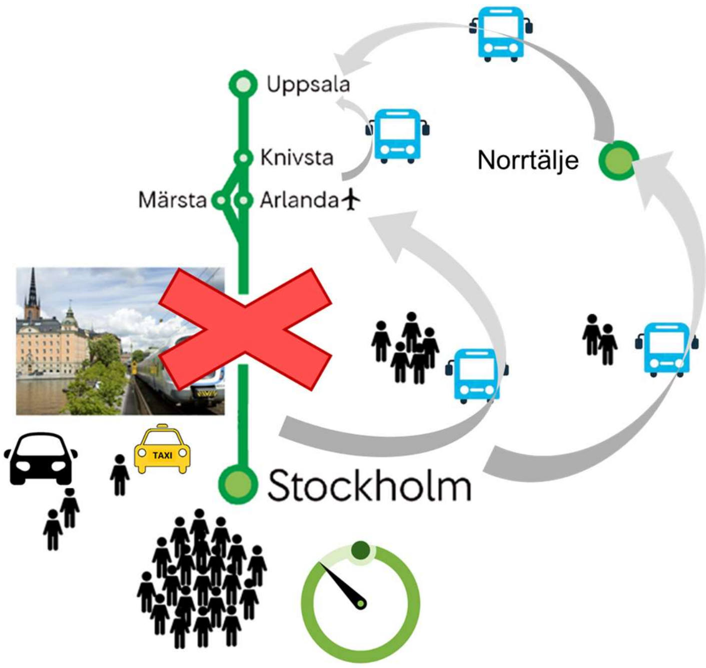

Figure 1. Illustration of current public transport disruption management.

4. Purpose, research questions and method

The purpose of this pre-study is to improve the efficiency, robustness and attractiveness of shared urban mobility by facilitating better real-time integration between fixed public transport services and demand-responsive taxi services. Specifically, the pre-study has focused on the role of taxi services as a means to reduce the negative impacts and costs caused by public transport disruptions. Disruptions are seen as one of the most negative aspects of public transport, and better disruption management can be expected to attract more travelers to public transport from e.g. private cars. The purpose is to develop a sustainable collaboration model, which requires that it is beneficial for all involved parties: (1) the public transport authority and operator(s), (2) the private taxi operator(s), and (3) the travelers.

Specifically, the pre-study addresses the research question: Can a system-of-systems involving real-time data sharing between the public transport operator and one or several taxi operators be a beneficial approach to handle public transport service disruptions?

The method used to answer the research question consists of three main parts:

1. stakeholder discussions,
2. literature review and state-of-the art analysis,
3. analysis of public transport and taxi data.

Stakeholder discussions

A stakeholder workshop was organized at KTH on 5 December 2018. Participants were Erik Jenelius and Matej Cebecauer from KTH, Stefan Thulin, Revenue Strategist at SLL, Rutger Hörndahl, Senior Technical Advisor at Scania, and Sven Anderzén, Manager Operations Support Systems, Keolis Sverige. A second workshop will be arranged during 2019 to discuss the outcomes of the pre-study and the road ahead towards a full project proposal.

Literature review

A review of literature related to business models and system architectures for MaaS systems and public transport disruption management strategies has been carried out.

Analysis of public transport and taxi data

The iMobility Lab within the Division of Transport Planning, KTH hosts large sets of data from taxis and public transport in the Stockholm area. The main data sources that have been used in the pre-study are:

- Taxi floating car data, containing GPS locations, time stamps, and hired/free status at an average frequency of 30 reports per vehicle per hour.
- Public transport automatic vehicle location (AVL) and automatic fare collection (AFC) data. These sources provide information about arrival and departure times, boarding and alighting passenger counts, at stops and stations.

Taxi GPS data provide a good source of real spatiotemporal information about the demand for demand-responsive services. Similarly, AVL and AFC data provide corresponding information about how the demand for conventional public transport varies with location and time. The spatiotemporal demand patterns for taxi and public transport services have been compared and combined in order to study the business potential of MaaS during disruptions.

5. Objective

As described in the application, the objective of this pre-study has been to investigate the potential for a full-scale project focused on integrating demand-based and line-based services into a multi-modal public transport system through sharing of real-time information. The pre-study has aimed to narrow the scope of the full-scale project to a well-defined setting. Specifically*, public transport disruption management through collaboration with taxi services* has been identified as an interesting area for further development.

6. Results and deliverables

6.1 Stakeholder discussions

At the workshop on 5 December 2018, discussions started by introducing the systems-of-systems (SoS) concept and its relevance in the area of urban mobility. We presented the main ideas of the pre-study (data sharing for better integrating between public transport and demand-responsive services), and the resources (data, knowledge, simulation tools) available at iMobility Lab, KTH.

During the discussion, several stakeholders highlighted the value of more demand-responsive services in the future. Ideally organized by contractors, the public transport authority (PTA) would like to be able to include demand-responsive services and ride sharing in the contracts.

We introduced two main use cases for public transport and taxi data sharing: (1) last-mile service and (2) disruption management.

Use case 1: Last-mile service

Last-mile service in low-density areas is a frequently highlighted application of integrated fixed and demand-responsive services. In such areas, taxis can serve as last-mile service connecting to a mass PT line. In this use case, taxi companies are subsidized to provide the service and the integrated service is included in the PT ticket. This door-to-door service encourages people to use PT + taxi instead of private car or taxi all the way.

The arrival time of each PT vehicle to the feeder stations can be predicted based on automatic vehicle location (AVL) data. With real-time automatic passenger count (APC) data, we know how many are on-board each PT vehicle. With automatic fare collection (AFC) data, we may even estimate the destinations of the passengers.

Within a real-time information-sharing platform, the PT operator transmits this information to the taxi companies or a neutral information hub. With this information, taxi companies can dispatch the appropriate number of vehicles to each station to pick up travelers. Accepted rides are confirmed to the PTA or the neutral information hub to keep track of the number of served travelers.

The stakeholders considered this use case as a good candidate for applying demand responsive service and ride sharing. However, from experiences with paratransit there is a risk of fraud when it comes to operators sharing origin, destination and travel time information with the PTA, in order to increase their revenue. The trips should not be arranged by the individual travelers, but instead go through the PTA to ensure that all travel information is correct.

Use case 2: Disruption management

Disruptions and the associated lack of information are perceived as one of the worst aspects of public transport, and a strong motivation for relying on a private car. Current state-of-practice in Stockholm is to handle disruptions on high-capacity lines through calling in bridging buses and travel cost reimbursements for travellers who would otherwise have incurred at least 20 minutes delay due to the disruption. Bridging buses are costly, often take significant time to arrive and cannot handle the passenger loads of a full metro or commuter train. Travel cost reimbursements also cost the PTA significant amounts each year.

In this use case, the PTA enters an agreement with one or several taxi companies to provide bridging services with taxis during PT disruptions. The main difference compared to the current reimbursement system is that the PTA rather than the individual travelers will arrange the transport, which can save time and costs. The purpose of the collaboration is to

1. Complement and potentially reduce the need of bridging buses
2. Reduce the costs of reimbursements and potentially fully replace them
3. Reduce the waiting times and the responsibilities of the individual travellers to arrange alternative modes of transport
4. Better utilize available taxi capacity through proactive dispatching and ride sharing

Similar to the last-mile use case, taxi companies are subsidized to provide the service and the integrated service is included in the PT ticket. Regarding who will provide services during disruptions, at least two options are available:

- The suppliers are contracted in advance
- The system is arranged like a market available for various contracted/not contracted providers that can bid for an amount of people they have the capacity to move at particular time.

The integrated disruption management service is illustrated in Figure 2, using a hypothetical disruption on the commuter train service between Stockholm and Uppsala as example. Disruption on trains on this line can affect 60,000 people. Even if some of the travellers will use alternative PT routes, many will wait until they can call a taxi. Ride sharing with taxis can help to decrease waiting times and costs.

When the disruption occurs, the PTA know that a train with x passengers has stopped at station n. With real-time APC data, we know how many are on-board the stopped PT vehicle. Evaluating historic disruptions, even more can be learned from historical data. With historical AFC data, we can estimate destinations; we know where and when passengers considered different alternative connections. The PTA transmits the information this information to the taxi companies or a neutral information hub. With this information, taxi companies can dispatch the appropriate number of vehicles to station *n* to pick up travellers. Taxi services are provided to downstream stations along the line. Accepted rides are confirmed to the PTA or the neutral information hub to keep track of the number of served travelers.

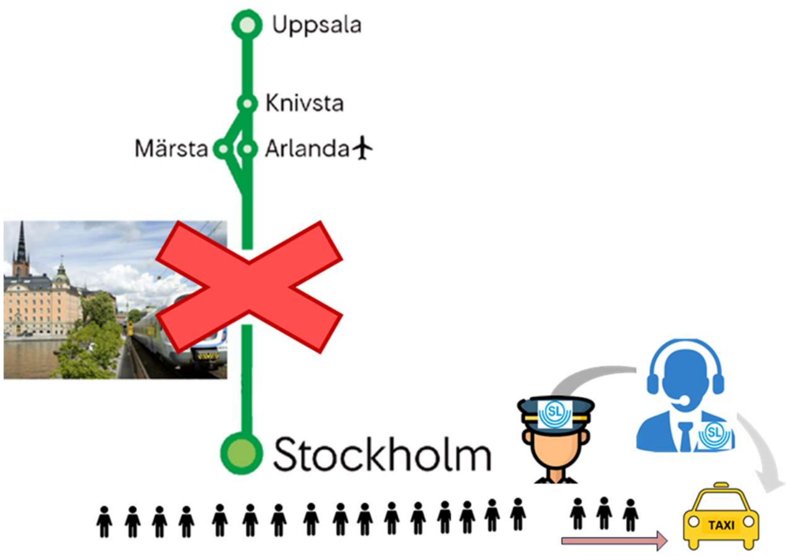

Figure 2. Illustration of disruption management through integrated public transport and taxi services.

The arrangements between the PTA and the taxi services in the two use cases are similar. The main difference lies in the permanency of the collaboration: In the last-mile case, taxi services would be continuously provided and integrated with public transport. In the disruption management case, the collaboration agreement would be triggered only during significant disturbances; at other times, the two actors would be free to plan their services independently.

The stakeholder discussions addressed some aspects to consider in an implementation of this use case:

- The service of the disrupted line is contracted to a certain PT operator. How to arrange that some other operators are able to take over the customers during disruptions?
- Ride-sharing can be problematic. How to select the people with close or on the way destinations from crowd. How can it work? It makes sense if travelers will not be served door-to-door but only to the planned stations along the line, if the further PT works fine from there.

In summary, the stakeholder discussions yielded important insights about the challenges and difficulties with a system-of-systems that involves the classic line-based PT and demand-responsive services. At the meeting we agreed that the two cases, disruption management and last-mile service, are good candidates for further development. The subsequent work in the pre-study has focused on the disruption management use case, since it has been less studied and is narrower in scope than the last-mile service case.

6.2 Literature review

Public transport and demand-responsive transport integration

Collaboration between public transport and taxi services are used e.g. in Sweden and the Netherlands to provide demand-responsive transport (DRT) services for passengers that have difficulty using regular public transport. Westerlund and Cazemier (2007) present several procurement models for contracting private taxi operators to ensure high quality of service. According to the report, about half of the taxi industry's revenue in Sweden comes from contract work and about 60% in the Netherlands. To attract more riders from suburban areas to public transport, PTAs must find adequate solutions to accommodate the first and last mile between the riders' home and the public transport stations. Possible solutions include operating a fleet of demand-responsive feeder vehicles or collaborating with local taxi service providers. In the U.S., public transport providers have started collaborating with Uber and Lyft to better coordinate their service offering (Murphy, 2016). While the services are convenient for the riders, they are often costly for the PTA and the riders (Stiglitz et al., 2018).

Taxi or similar ride-hailing services (e.g. Uber and Lyft) are also common components of mobility-as-a-service (MaaS) systems. Following Hietanen (2014), MaaS can be defined as "a mobility distribution model in which a customer's major transportation needs are met over one interface and are offered by a service provider". According to Smith et al. (2017), The PTA's interest in MaaS comes from their desire to find new cost-efficient ways of increasing PT's modal share. However, MaaS is a complex transformation of the transport system that may require new forms of public-private partnerships (PPPs) where private actors play a larger role in the creation of public value.

Public transport disruption management

Based on the outcomes of the workshop, the pre-study has primarily focused on the business case of disruption management. The following review of research literature and current state-of-the-art is focused on this topic.

Railway systems are sensitive to unexpected events such as infrastructure breakdowns, technical failures, severe weather conditions and accidents. Such events can lead to rapid, sometimes long-lasting degradation of service and significant delays for travelers. Using a definition originally borrowed from aviation, a disrupted situation is an operational state in which the variation from an original plan is significant enough to necessitate replanning (Clausen, 2007).

Depending on the type of disruption, there are several techniques to restore service in order to minimize the negative impacts for travelers. Pender et al. (2013) conduct a survey among 71 international public transport agencies regarding their strategies for managing unplanned service disruptions. The responses show that the approaches vary depending on if the disruption is a train failure or a line blockage. In the case of line blockages, bus bridging is the dominating strategy (85% of respondents). It is common, however, to use different approaches depending on location, time, duration, type of event, etc. Other approaches include single tracking/bypassing (51%), rerouting trains (23%), diverting to other lines (35%) or parallel PT (47%), and improving frequency of parallel PT (17%). The approach of hiring taxis is used by only a small fraction of respondents (5%).

A weakness of the bus bridging approach is that the buses and drivers must be either kept on stand-by or moved from their original lines. It often takes a substantial amount of time for the buses to arrive, and the normal schedules need to be rescheduled. As a result, passengers often have a negative attitude towards bus bridging (Zeng et al, 2012). In Munich and Berlin, the tram operators handle short-term disruptions through collaboration with a local taxi operator to provide faster rail replacement service. Zeng et al. (2012) report that the tram operators expect a reduced recovery time by using taxis rather than buses as rail replacement service. Since taxis are operating over the entire city, taxis can be assembled considerably faster. In addition, using taxis allows the tram system control centers to concentrate on recovering the system.

The recovery method used by the Munich tram system works as follows: Taxis are ordered only if the disruption is expected to last less than one hour (for longer durations, bus bridging is still a viable option). The disruption manager calls the taxi center to order a needed number of taxis once the duration of a disruption is assessed. The taxis arrive at the impacted station and take the passengers to the next normally operated tram station or any nearby bus or metro station. Deviation from the route is not allowed. The tram company pays the taxi services. Passengers are informed via announcements on the real-time information system, and are advised not to call for taxis on their own; those who do have to pay for the service. Figure 3 shows the recovery process in detail (Zeng et al., 2012).

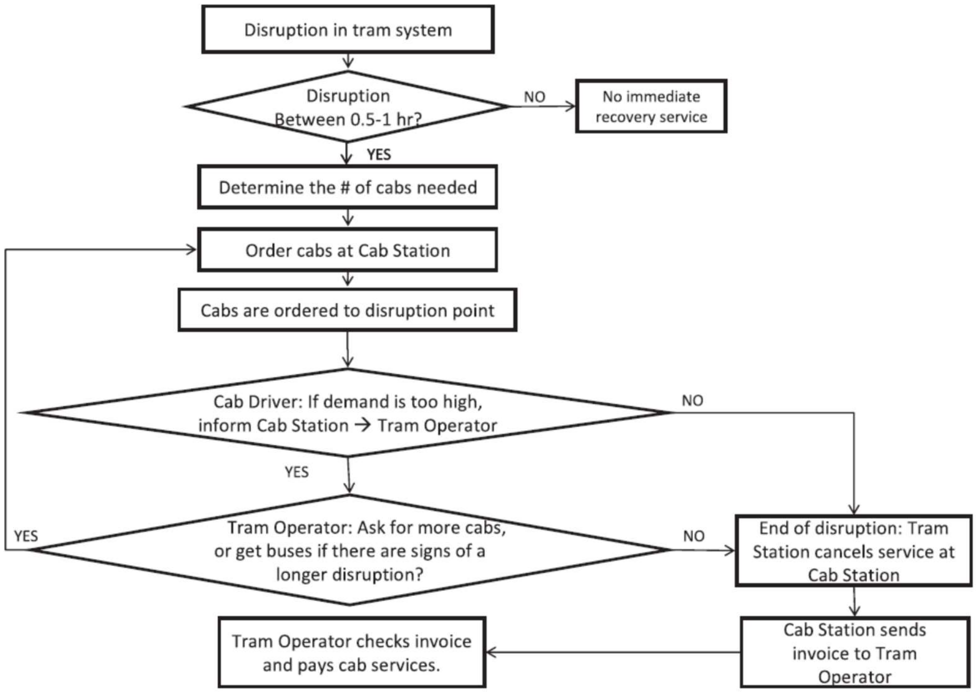

Figure 3. Disruption management framework based on taxis for Munich tram network. Source: Zeng et al. (2012) (modified from Friess, 2009).

Taxis for public transport disruption management

Taxi-based public transport disruption management represents a system-of-systems that integrates the public transport system and the taxi system to achieve a higher level of service than if each system acts independently. In order to achieve a sustainable system-of-systems, the outcome must be beneficial for all involved actors. Zeng et al. (2012) note that the PTA and the taxi operator see the situation from different perspectives:

1. The objective of the PTA is to provide a continuous high quality service for its passengers while keeping the recovery costs within some constraints. The PTA thus needs to decide if it is worthwhile to use taxis for recovery service when passenger service level and recovery costs are balanced.
2. For the taxi company, the feasibility of providing sufficient taxi capacity on short notice is uncertain and comes at a cost. Thus, the taxi company must weigh the benefits of providing the needed taxis against the associated costs.

In current practices in Munich and Berlin, the decisions are made in an ad hoc fashion. To approach the problem analytically, Zeng et al. (2012) develop a series of mathematical models to capture the critical decision elements and derive some insights on how the two parties should act and what factors has the most influence on the decisions. It is assumed that the tram company has pre-selected a taxi company for possible transport recovery services. Further, every customer wants to maximize his/her utility by deciding whether to stay and wait for the tram replacement service or to leave. The tram company faces two decisions: (1) whether to use the taxi service in the event of disruptions; and (2) if the taxi service is used, how to compensate the services so that the taxi company is not only willing to collaborate by finding the needed number of taxis but also has incentive to provide as fast recovery as possible. Meanwhile, the taxi company can prioritize and select available vehicles to provide the recovery service and may be able to adjust the efforts and difficulty based on the tram company's needs.

Based on the proposed mathematical models and numerical examples, Zeng et al. (2012) observe that the tram operator's decision whether or not to collaborate with the taxi company largely depends on the service payment rate they are willing to offer and the average taxi service time for each round trip. Further, the benefits of both parties under collaboration can reach an equilibrium, which the tram operator can use to determine the optimal payment rate. Finally, a pricing scheme with a fixed payment rate is often favorable and is quite robust to changes in all the input parameters.

Fang and Zeng (2015) continue the analysis of the contract between a PTA and a taxi operator for disruption recovery service. The two actors' individually optimal decisions and their interactions through a negotiation process are examined. The contract specifies a pre-determined reserved quantity of taxis prior to the disruption to ensure available resources for the recovery effort. A game theoretic model is developed to to determine the reservation capacity, the consequences if the reserved capacity cannot meet the demand, and how the two parties should interact to achieve agreed-upon terms for capacity and compensation.

Fan and Yang (2019) analyze the replacement service options for providing quick response and efficient service during unplanned disruptions in urban public tram systems from the perspective of environmental impacts. The framework is used to determine whether to provide a replacement service, and whether taxis or buses should be selected as the service vehicles. The trade-off between the carbon emission and financial cost in the presence of different passenger behaviors is taken into consideration. Results from numerical studies indicate that taxis have a better environmental effect in reducing additional carbon emission, although the service is costly.

Yuan et al. (2018) present a model and technical solution method for public transport disruption management utilizing multimodal resources (buses, taxis, etc.) based on the availability of real-time AFC data about travel demand (Figure 4). The framework is based on three operations: reallocation of vehicles among lines, spatial rerouting of vehicles (buses, trains, taxis), and temporal rescheduling. The data-driven evaluation results show that the solution improves the ratio of served passengers (RSP) substantially compared with existing solutions.

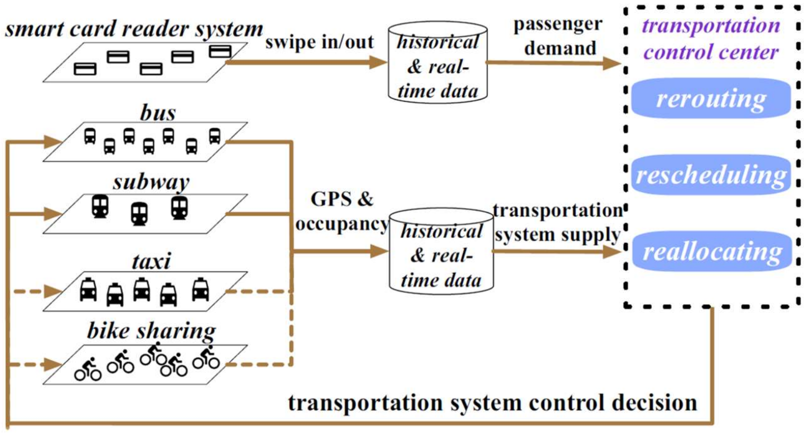

Figure 4. Disruption management framework "eRoute" Source: Yuan et al. (2018).

6.3 Data analysis

The preliminary data analysis aims to investigate available public transport and taxi data sources in order to reach a valuable and achievable scope for a full project.

Data sources

Taxi floating car data: For several years up to August 2016, floating car data (FCD) were collected from ca. 1,500 taxis operating in the Stockholm region. Each vehicle reports its id, GPS coordinates, timestamp, and information whether it is occupied or not with an average frequency of once every two minutes. There is no information about the true origin and destination of the trip, which can only be inferred based on changes of the taxi's status.

Public transport automatic vehicle location (AVL), automatic passenger count (APC) and automatic fare collection (AFC) data: AVL data contain most metro, train, tram, and bus trips. The coverage by APC data is around 10% of the buses, which makes it difficult to measure the demand accurately. Fortunately, the iMobility Lab has been granted access to the complete smart card data from Region Stockholm PTA (Trafikförvaltningen). This allows us to get an almost complete picture of the travel demand. Only about 1% of all trips are not recorded in the smart card data. Processing of tap-in data to multi modal origin-destination journeys is currently being finalized at the iMobility Lab. This public transport demand data source has a high potential for a full project proposal.

Data fusion of public transport smart card data and taxi probe data is smooth as they both contain geographical coordinates and timestamps. Every trip or journey contains origin and destination information. Demand from public transport can be aggregated based on stop/zone/area and day/time.

Case study: Metro disruption

To demonstrate the effects of public transport disruptions, we selected a case study involving 23 metro stations located on the red line in Stockholm (see Figure 5). The case study simulates a disruption during which the stations cannot be served by metro trains; in other words, there is no metro connection to transfer hub Slussen. The Slussen station is the closest functioning station from which travelers can continue their trips. Demand data from one historical day (1st April 2016) are selected. The demand from the disrupted station during the morning peak 06:00 – 10:00 is about 40,000 travelers.

Figures 5(a) shows the origins of trips from the stations affected by disruption during the morning peak. Figures 5(b) shows the destination stations of trips from the affected metro stations.

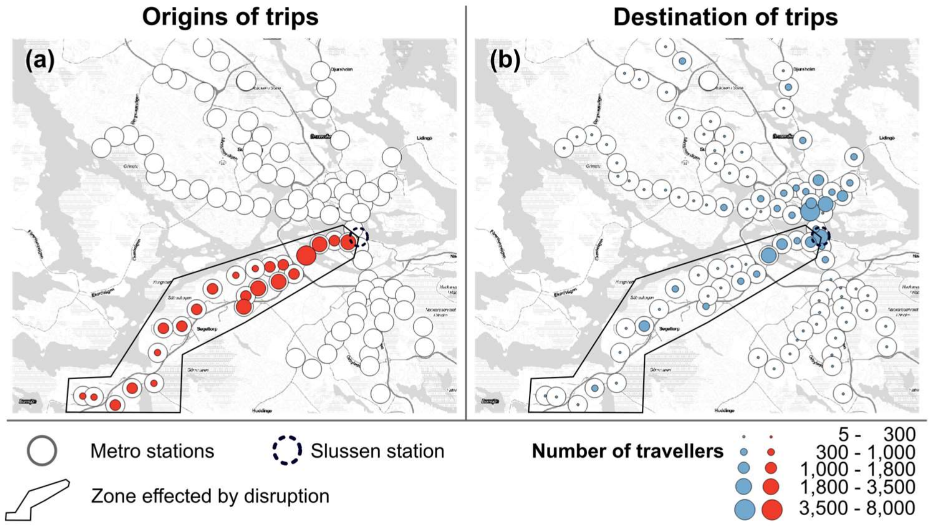

Figure 5. Visualization of the case study OD matrix for 1st April 2016.

Origin and destination inference

Taxi data: The taxi data do not contain information about the travelers' true origins and destinations, but we infer these based on the changes of the taxis' status. The spatial distribution of the inferred origins and destinations for the morning peak on 1st April 2016, which is the same day and period as considered in the disruption case study above in Figure 5, is shown in Figure 6. Most trip origins and destinations are located in the city center or at the airports.

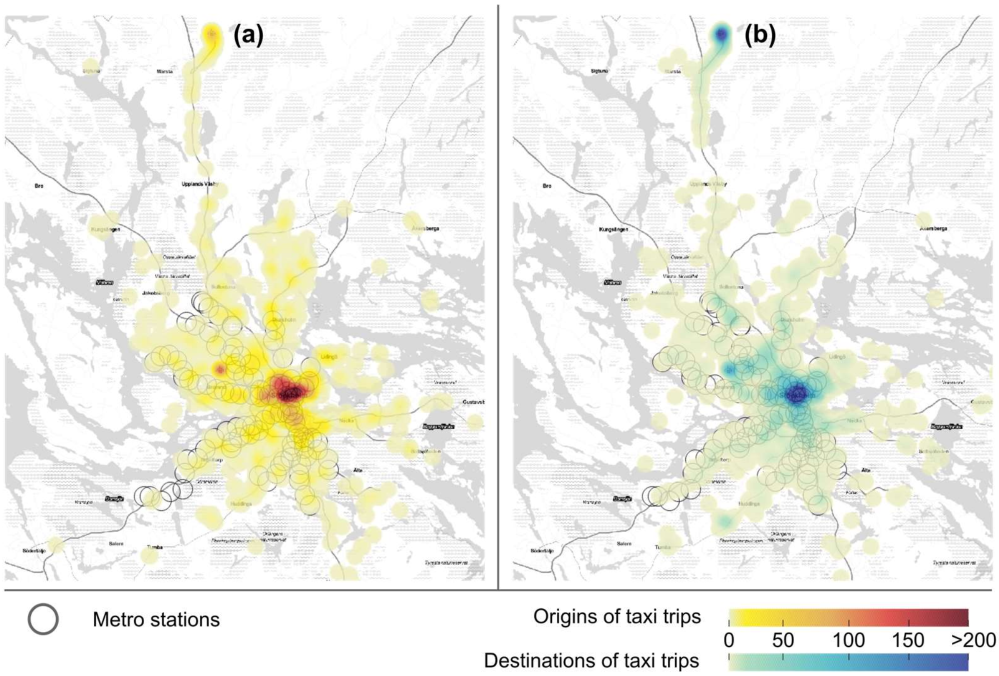

Figure 6. Spatial distribution of taxi trips (a) origins and (b) destinations during period 06:00–10:00 on 1st April 2016.

AFC data: The public transport ticket system is Stockholm is a tap-in only system; thus, the tap-outs have to be inferred to get the complete trip information. Processing the Access data is a computationally and time consuming task. When inferring the tap-out locations, all multimodal tap-in data are used. We use a next tap-in radius to infer the stop with the same line as the previous tap-in. The closest such station is considered as the tap-out location. Figure 7 shows the spatial distribution of PT trips during the morning peak on 1st April 2016. It is noticeable that the tap-ins are more geographically spread out than the tap-outs which are concentrated to the city center.

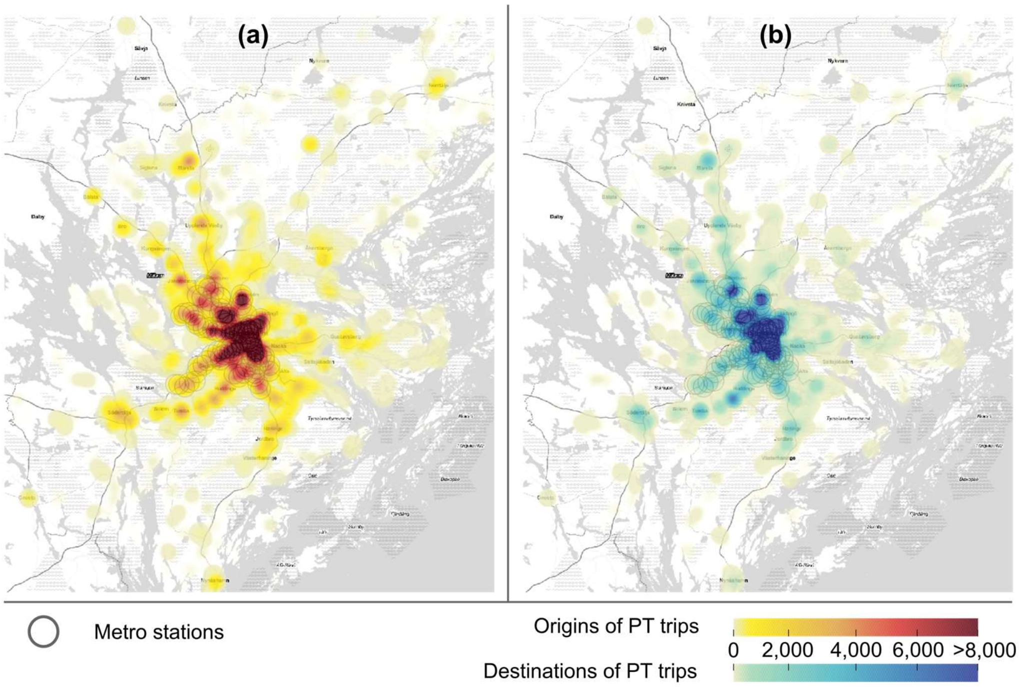

Figure 7. Spatial distribution of public transport trips (a) origins and (b) destinations during period 06:00–10:00 on 1st April 2016.

The AFC data provide demand for all modes of public transport including ferries, trains, trams, metro and buses. This demand has spatio-temporal attributes and can be used for estimating a multi-modal demand model. Taxi data provide spatio-temporal attributes as well and can thus be used in the same way. Both demand sources are in general able to provide destinations and multimodal OD demand for historical days. A demand prediction model can be built based on the historical patterns. A demand model can be useful for e.g. network design or long-term disruption planning. If it will be needed such a demand model can be developed during a follow-up project.

Disruption management simulations

We have simulated disruption management strategies and estimated the waiting times and total travel distance/time as indicators of costs. The aim is to transfer the travelers from their origins to destinations represented here by metro stations. For the morning peak, only the demand from the affected area is considered (see Figure 5(a)).

Two different disruption management strategies are considered here. In the first strategy, travelers order the door-to-door service (station-to-any-station here) from taxi providers directly. In the second strategy, the PTA organizes transfers only for all trips from the affected stations to the affected stations and to Slussen station (accumulating all trips with destinations beyond Slussen) in the morning peak. We do not consider ride sharing here.

In order to compare the two strategies, we estimate and analyze the average waiting time (quality and satisfaction measure) as well as the total serving time (estimate of operational costs). The individual trips and real arrival times of travelers are considered here. The travelers are entering the simulation based on the spatial and time attributes extracted from AFC data. For each tap-in the location and entering time is defined. The desired destination is the tap-out of the particular trip. We vary the number of taxi vehicles available according to the following values: 200, 500, 1000, 2000, 4000 and 6000. The number of 6000 taxis represents the approximate number of taxis in the Stockholm area.

Figure 8 shows the waiting time in hours for the two disruption management strategies. The strategy where travelers call taxis themselves as a door-to-door service (blue line in Figure 8) lead to 5 times longer waiting times in the case of 6000 taxis; with the traveler-centered strategy the waiting time is 6.85 hours and with the PTA strategy (orange line in Figure 8) it is 1.32 hours. Even the PTA strategy takes a long time. In this case study, however, we considered that all travelers desire to be transferred. In a real-world setting, some share of the travelers will search for PT alternatives or decide to work from home as the morning peak is affected. This can be different in the afternoon when all people desire to get home. With this pre-study simulation, we examined the importance and effects of two different disruption management strategies and outcomes regarding waiting time or satisfaction can be significant.

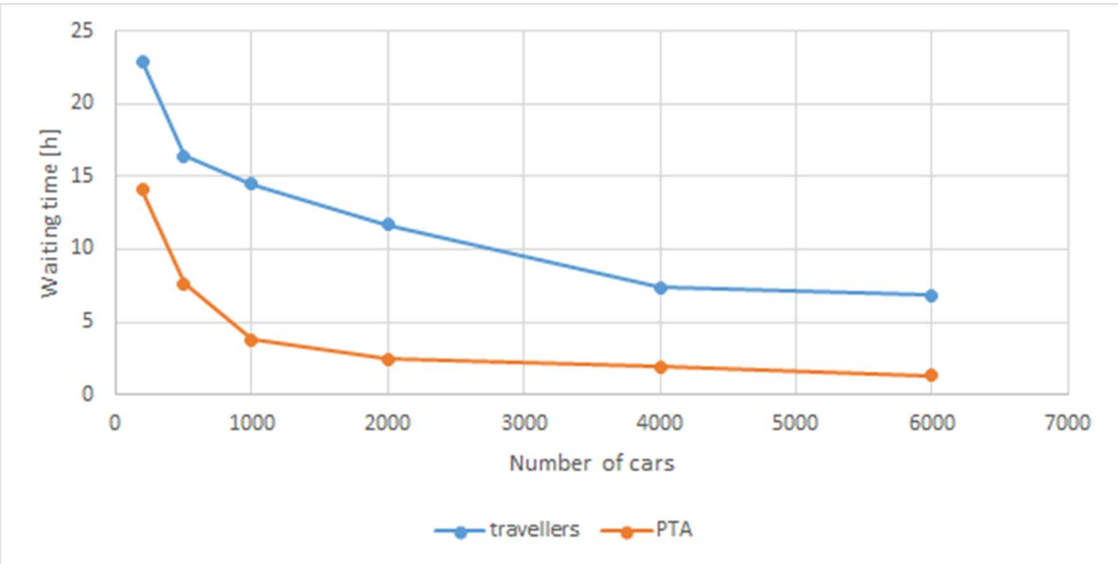

Figure 8. Waiting time for the two disruption management strategies (traveler-centered and PTA-centered).

Finally, we examine the total vehicle kilometers travelled which is 235,708 km for the traveler-centered strategy and 204,962 km for PTA-centered strategy. The difference is 30,744 km, which can be used for estimating the operational costs. The PTA strategy can save costs and decrease waiting times which can be appreciated by travelers.

However, the waiting time of 1 hour is still significant, and there is space for possible improvements considering ride sharing. Imagine that instead of transporting one person, the taxi car will transport three at the same time. It can results in 1/3 of the waiting time which will be about 20 minutes. This may be satisfy most travelers and can also decrease the costs to 1/3. This highlight and numerically supports the idea of smart disruption management organized by the PTA, particularly with ride sharing involved.

6.4 Contribution to FFI and SoSSUM

The pre-study contributes to the general goal of FFI to reduce the environmental impacts of road transport. Disruptions and the associated lack of information are perceived as one of the worst aspects of public transport, and a strong motivation for relying on a private car. By providing solutions for more efficient and robust management of public transport disruptions, the pre-study helps to attract more travelers to public transport, which will contribute to a reduction of environmentally hazardous emissions such as CO2 and NOx.

The pre-study contributes to the goals of SoSSUM by investigating the potential for a smart urban mobility solution, namely public transport disruption management with real-time demand data, based the SoS thinking. The developed solution is intended to increase the efficiency of the transport system during disruptions, thereby increasing the reliability and robustness of the system. The key idea is to use existing resources more efficiently by calling in flexible taxi services to support the disrupted public transport services, reducing the need for less flexible reserve capacity such as bridging buses.

The objectives of the pre-study have been reached. The project has successfully narrowed the scope to find a use case for further development in a full-scale project. Stakeholder discussions, literature review and data analysis suggest that the use case has potential to be of practical value. The pre-study did not manage to attract representatives from the taxi industry to the stakeholder discussions. For a full-scale project, a consortium should include at least one such partner to ensure that the developed system is useful and valuable for all involved actors.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Knowledge on the potential of public transport disruption management with DRT through SoS thinking.
Be passed on to other advanced technological development projects	X	Prototype of working platform for disruption data sharing and traffic management should be implemented in follow-up project.
Be passed on to product development projects		
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions	X	Public transport disruption management with DRT may require adjustments in regulatory or procurement procedures.

Project leader Erik Jenelius participated in the Third Swedish Workshop on the Engineering of Systems-of-Systems, 22 November 2018 at Linköping University.

A second stakeholder workshop will be arranged during 2019 to discuss the outcomes of the pre-study and the road ahead towards a full project proposal.

As an outcome of the pre-study, a research collaboration has been initiated with French research institute Vedecom. Vedecom researcher Dr. Tatiana Babicheva visited the Division of Transport Planning, KTH during May 2019 and began a joint research effort on optimal strategies for integrated demand-responsive and fixed public transport during disruptions. Dr. Babicheva has a PhD in Mathematics and her research interests include ITS, transportation network analysis, traffic simulation, path finding and optimisation.

7.2 Publications

One publication has been produced as a result of Dr. Babicheva's visit to the Division of Transport Planning, KTH:

Babicheva, T., Cebecauer, M., et al. (2019) "Empty vehicle redistribution with time windows in autonomous taxi systems", to be submitted.

We plan for at least one more scientific publication to be produced during 2019.

8. Conclusions and future research

Within this pre-study project, we have addressed the following three main goals in a Swedish context, which are necessary for developing a full-scale SoSSUM project proposal in relevant and realistic direction:

- To study the potential of combining real-time taxi and public transport demand and supply data to enhance the efficiency of both services.
- Identify potential business models, ways of cooperation and sharing of trips or vehicles between actors that are currently independent (individuals, taxi companies, public transport operators), which should be studied in the full project.
- Round-table discussions with involved actors (public transport authorities, local traffic authorities, public transport operators, taxi companies).

The stakeholder discussions, literature review and data analysis suggest that a system-of-systems involving taxi and public transport is a promising approach for public transport disruption management that merits further development. In this approach, the PTA enters an agreement with one or several taxi companies to provide bridging services with taxis during PT disruptions. Through real-time sharing of travel demand data the SoS framework can better utilize available taxi capacity through proactive dispatching and ride sharing. Real-world examples and simulation studies suggest that such an approach can successfully reduce traveler waiting times and environmental impacts, whereas the cost savings for the PTA need further study.

Further research is needed to develop the business models of SoS for disruption management in a Swedish setting. This involves an in-depth analysis of the incentives of the stakeholders given current markets and regulations. Further work should also be directed towards a pilot study. Simulation can be tool to investigate different business models and situations. With AFC data (e.g., Stockholm Access data) it is possible to estimate the amount of the people on the train and we can estimate the destinations for them considering historical data.

For a full-scale project, a consortium should include at least one taxi company to ensure that the developed system is useful and valuable for all involved actors. Further, a full consortium should include a partner with the capacity of developing a prototype software solution for data sharing between public transport and taxi operators.

9. Participating parties and contact persons

The project was carried out by the Division of Transport Planning, KTH Royal Institute of Technology. Contact person: Docent Erik Jenelius, project leader, jenelius@kth.se,

+46 8 7908032. Postal Address: Dept. of Civil and Infrastructural Engineering, KTH, SE-100 44 Stockholm.

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