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TRANS-FORM

Smart Transfers through Unravelling Urban Form and Travel Flow Dynamics

ERA-NET on Smart Cities and Communities



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Summary

Smart cities and communities rely on efficient, reliable and robust transport systems. The TRANS-FORM research project contributes to a better understanding of how people move in different levels of the public transport network and offer new techniques to adjust public transport services to respond to actual demand levels. The overarching objectives of the project are to understand transferring dynamics in multi-modal public transport systems and to develop insights, strategies and methods to support decision makers in transforming public transport usage to a seamless travel experience by using smart data. A multi-level approach is adopted in this project for monitoring, mapping, analysing and managing urban dynamics in relation to interchanging flows. The project develops strategies to coordinate transfers by taking into consideration passenger transaction data and deploy short-term predictions of passenger flows based on historical and prevailing travel patterns that partially rely on input from the behavioural models. In cooperation with local transport operators and authorities, three cases studies in the Netherlands, Sweden and Switzerland measure how travellers transfer within terminals, urban and regional networks in order to develop methods for predicting passenger flows, quantify the reliability of passenger experience and evaluate strategies for improved coordination between travel modes, especially in case of disturbances.

Zusammenfassung

Intelligente Städte und Gemeinden sind auf effiziente, zuverlässige und robuste Verkehrssysteme angewiesen. Das Forschungsprojekt TRANS-FORM trägt zu einem besseren Verständnis der Mobilität von Menschen auf verschiedenen Ebenen des öffentlichen Verkehrsnetzes bei und bietet neue Techniken, um die öffentlichen Verkehrsdienste an die tatsächliche Nachfrage anzupassen. Übergeordnetes Ziel des Projekts ist es, die Übertragung von Dynamik in multimodalen öffentlichen Verkehrssystemen zu verstehen und Erkenntnisse, Strategien und Methoden zu entwickeln, die Entscheidungsträger dabei unterstützen, die Nutzung öffentlicher Verkehrsmittel mithilfe intelligenter Daten in ein nahtloses Reiseerlebnis umzuwandeln. In diesem Projekt wird ein mehrstufiger Ansatz zur Überwachung, Kartierung, Analyse und Steuerung der Dynamik von Städten in Bezug auf den Austausch von Flüssen verfolgt. Das Projekt entwickelt Strategien zur Koordinierung von Transfers unter Berücksichtigung von Passagiertransaktionsdaten und zur Bereitstellung kurzfristiger Vorhersagen von Passagierströmen auf der Grundlage historischer und vorherrschender Reisemuster, die teilweise auf Eingaben aus den Verhaltensmodellen beruhen. In Zusammenarbeit mit lokalen Verkehrsbetrieben und Behörden wurde in drei Fallstudien in den Niederlanden, Schweden und der Schweiz gemessen, wie Reisende innerhalb von Terminals, städtischen und regionalen Netzen umsteigen, um Methoden zur Vorhersage der Passagierströme zu entwickeln, die Zuverlässigkeit der Passagiererfahrung zu quantifizieren und Strategien für zu bewerten verbesserte Koordination zwischen den Reisemodi, insbesondere bei Störungen.

Résumé

Les villes et les collectivités intelligentes reposent sur des systèmes de transport efficaces, fiables et robustes. Le projet de recherche TRANS-FORM contribue à une meilleure compréhension de la façon dont les gens se déplacent à différents niveaux du réseau de transport en commun et propose de nouvelles techniques pour adapter les services de transport en commun à la demande réelle. Les objectifs généraux du projet sont de comprendre la dynamique de transfert dans les systèmes de transport en commun multimodaux et de développer des idées, des stratégies et des méthodes pour aider les décideurs à transformer l'utilisation des transports en commun en une expérience de voyage



transparente en utilisant des données intelligentes. Une approche à plusieurs niveaux est adoptée dans ce projet pour surveiller, cartographier, analyser et gérer les dynamiques urbaines en relation avec l'échange de flux. Le projet élabore des stratégies pour coordonner les transferts en tenant compte des données sur les transactions de passagers et déploie des prévisions à court terme des flux de passagers sur la base des schémas de déplacement historiques et dominants qui reposent en partie sur les informations fournies par les modèles comportementaux. En coopération avec les opérateurs de transport locaux et les autorités, trois études de cas aux Pays-Bas, en Suède et en Suisse mesurent la manière dont les voyageurs se déplacent dans les terminaux, les réseaux urbains et régionaux, afin de développer des méthodes de prévision des flux de passagers, de quantifier la fiabilité de l'expérience des voyageurs et d'évaluer les stratégies de gestion. amélioration de la coordination entre les modes de transport, notamment en cas de perturbations.



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List of abbreviations

SFOE	Swiss Federal Office of Energy
EPFL	Ecole Polytechnique Fédérale de Lausanne
TUD	TU Delft
BTH	Blekinge Institute of Technology
LiU	Linköping University



1 Introduction

Smart cities and communities rely on efficient, reliable and robust transport systems. Managing urban public transport systems is becoming increasingly challenging with a pronounced shift towards multiply actors operating in a multi-modal multi-level networks. This project for the development of an integrated passenger-focused management approach which takes advantage of multiple data sources and state-of-the-art scheduling support.

TRANS-FORM, a cooperation between universities, industrial partners, public authorities and private operators, develops, implements and tests a data driven decision making tool that supports smart planning and proactive and adaptive operations. The tool integrates new concepts and methods of behavioural modelling, passenger flow forecasting and network state predictions into real-time operations.

New empirical knowledge and modelling foundations are developed by undertaking a multi-level approach for monitoring, mapping, analysing and managing urban dynamics in relation to interchanging travel flows. Analysis of pedestrian and traveller flows at the hub, urban and regional networks is facilitated by data secured from case studies in Switzerland, the Netherlands and Sweden, respectively. Project outcomes will allow policy makers and service providers to better understand how travel demand evolves, model traveller flows and interchange activities, develop different strategic and operational measures, and evaluate their impacts.

2 Context

2.1 Background / State of the art

The abundance of various data sources such as electronic payment systems opens up new possibilities to gain new knowledge on urban flow dynamics in general and transfer patterns in particular. Transferring – interchanging between public transport vehicles – is a major source of travel uncertainty. Previous studies suggested methods to coordinate services in the planning (e.g. Guevara and Donoso, 2014) and real-time operations (e.g. Dessouky et al., 2003; Neshelli and Ceder, 2015). Public transport networks are increasingly complex and multimodal and thus challenging to manage, while it is increasingly important that the networks are robust (Törnquist Krasemann, 2012).

Smart card automated fare collection systems have become in the last decade the primary mode of payment in many public transport systems. While their main purpose is to efficiently collect revenue, they also produce large quantities of detailed data. With such data, mobility patterns and sequence of activity of individuals can be estimated, modelled and forecasted (Danalet et al., 2014). Smart data can also be used in each of the three planning levels: strategic, tactical and operational (Pelletier et al., 2011). Passenger data analysis provides a better understanding of user behaviour (Bagchi and White, 2005; Trépanier et al., 2007; Nassir et al., 2015), origin-destination demand (Munizaga and Plama, 2012; Hänseler et al., 2017), service quality (Boyle et al., 2000), urban form and impact of planning policies (Cats et al., 2015) and frequency and timetable design (Utsunomiya et al., 2006). However, the potential of smartcard data in real-time management remains largely unexplored.

2.2 Motivation of the project

The use of smart data generates a great potential for monitoring the actual transport demand and for generating more frequent and reliable forecasts to support real-time management. The behaviour of



travellers in public transport, in particular during disruptions of the service, plays a fundamental role that has to be carefully considered and forecasted (Chorus and Bierlaire, 2013; Cats and Jenelius, 2014; Schmidt and Schöbel, 2015). By integrating information from these models with more traditional sources such as counting systems and flow measurements, mobility patterns can be identified and used to provide improved input for decision processes and further aiding traveller information (Ben-Akiva et al., 2001).

2.3 Goals

The overarching objective of the TRANS-FORM project is **to better understand transferring dynamics in multi-modal public transport systems and develop insights, strategies and methods to support decision makers in transforming public transport usage to a seamless travel experience by using smart data**. This objective can be divided into four goals addressed by WPs1-4 as follows:

- Goal 1 Better understand the characteristics and evolution of traveller flow dynamics at three different geographical scales - transport hub, urban and regional network layers - and their integration;
- Goal 2 Provide traveller-focused tools for measuring and modelling passenger interchange activities;
- Goal 3 Develop innovative methods for planning and operating robust services including real-time and integrated strategies that involve forecasting passenger behaviour;
- Goal 4 Develop, apply, demonstrate and evaluate innovative transfer strategies under various scenarios and case studies. Practical recommendations will be drawn based on research findings.

3 Approach and methodology

3.1 Approach of the project

The innovation of the project is to introduce a **(i) real-time coordinated, (ii) multi-actor integrated and (iii) demand-driven approach** that can deal with the above-mentioned issues. This is achieved by transforming the operational challenges in the urban transport environment into new opportunities for advanced transport solution development:

- i. **Real-time coordination.** The project aims to move from tactical to real-time coordination. Many operators already use modeling techniques to coordinate transfers at the tactical planning phase, when designing timetables (e.g. Hadas and Ceder, 2010). However, service dynamics often require real-time interventions to support a seamless travel experience in particular under daily disturbances and congestion situations as well as under disruption of the service in case of severe incidents (Cats et al., 2011; Muñoz et al., 2013).
- ii. **Multi-actor integration.** The transfer strategies proposed in the project consider the different actors involved and identify integrated traffic management plans. National, regional and local public transport systems are interlinked, yet controlled by different parties. To offer a seamless service, the operational decision-making needs to be coordinated. However, in terms of both of computational and organizational complexity, this is challenging due to the conflictive objectives of the operators. The project proposes decision-support functionalities considering the contrasting perspectives of the operators and integrated traffic management strategies.



- iii. **Demand-driven approach.** The project gears the services towards travellers rather than the infrastructure. The focus has been conventionally on the operator perspective and the consequences for the fleet and crew management (Dollevoet et al., 2014). While the majority of public transport scheduling/re-scheduling approaches assume traveller behaviour to be deterministic, their behavior may highly depend on the availability of alternative services (Parbo et al., 2014). The project focuses directly on travellers' perspective and their experienced quality of service which can readily be achieved and measured given the presence of real-time information and predictions concerning travel flows.

3.2 Methodologies

In order to achieve the innovative approach, the project **combines methodologies from different fields**. Data mining and transport network analysis are used to investigate network flow dynamics at different scales. Mathematical behaviour modelling is used to represent interchange activities. In particular traffic flow modelling, origin-destination demand estimation, route choice and behaviour modelling will be integrated into a joint framework. The transfer strategies are developed using methodologies from traffic management, control theory and optimization. Simulation techniques, robust and sensitivity analysis are used to evaluate the developed methods.

To address the complex system in which different operators are interlinked, this project adopts a **multi-level approach for monitoring, mapping, analysing and managing urban dynamics in relation to interchanging flows**. In this approach, specifically, the following three levels at different geographical scales are identified (Figure 1): (1) *Transport hub network*, microscopic intra-station pedestrian flows including interchanges, (2) *Urban network*, inter-station, intra-urban passenger flows, and (3) *Regional network*, inter-station, inter-urban passenger flows. The novelty of the multi-level multi-modal approach will allow us to develop an integrated real-time traffic management model based on the availability of smart data unravelling the underlying passenger flow characteristics and activity distributions. The multi-level framework developed in the project is then used for real-time traffic management geared towards a seamless travel experience.

The project **develops strategies to coordinate transfers and deploys short-term predictions of passenger flows, based on historical and prevailing travel patterns** that rely on both passenger transaction data and input from behaviour models. Prediction models consider and reflect the uncertainty in inputs, modelling assumptions and parameters. This allows us to adequately assess the total welfare benefits of coordinating transfers by considering total travel time gains or losses and operational constraints.

The project **develops its own tools** to implement the integration of multi-level models and to visualize the model outputs from different scenarios with the developed strategies. The integration tool allows us to implement the models at three different scales by defining sequences and converting the input/output among the models. The visualization tool aims to nicely show the results of the impact of proposed approach and to help the decision-making.

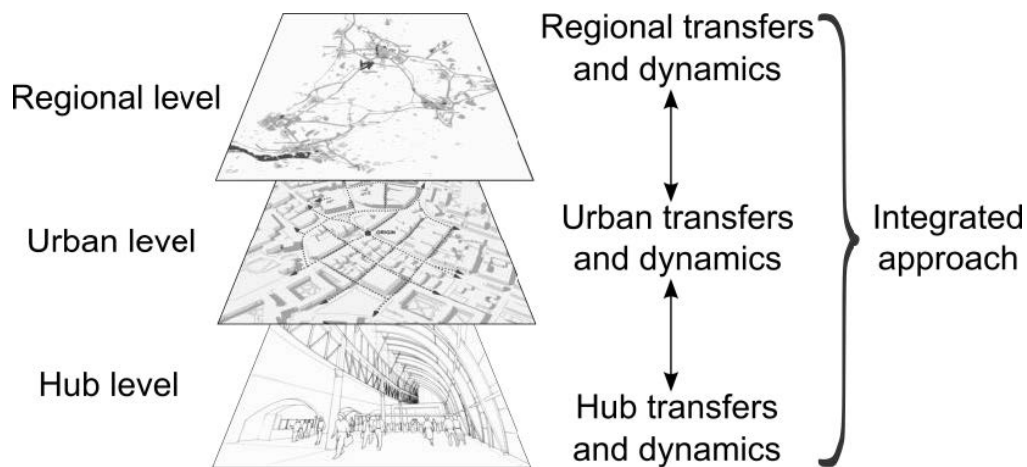


Figure 1: A multi-level approach the project proposes. Urban flow dynamics of three different levels are described in relation to interchanging flows.

3.3 Applications and case studies

The development of new empirical knowledge and modelling foundations for each of transferring levels of analysis – hub, urban and regional – is facilitated by data secured for the project from three case studies, as follows:

1. **Hub (Lausanne, Switzerland)** – understanding behavioural patterns using the hub information and video data of Lausanne train station from the national rail transport company (SBB, the owner of facilities, data secured by previous projects performed by EPFL).
2. **Urban (Haaglanden, the Netherlands)** – inferring passenger transfers for a light rail, tram and bus network; in cooperation with the urban public transport operator (HTM), network of rail operators (RailForum) and the city of Den Haag. Interfaces with intra-station and higher-level connections.
3. **Regional (Skane-Blekinge, Sweden)** – assessing passenger flows in the interface between regional and national train services; in cooperation with the railway traffic and infrastructure manager (Trafikverket), regional service provider (Blekingetrafiken) and regional authority (Region Blekinge), and municipality (Karlshamn). The robustness of train and connecting services is explicitly addressed.

The goal of these case studies is to measure transfer dynamics in order to develop methods for predicting passenger flows, quantify the reliability of passenger experience and evaluate strategies for improved multi-modal coordination, especially in case of disturbances. Understanding behavioural aspects and the flow dynamics at each of these network layers can support and enhance the modelling and forecasting of flows at the other layers. By considering the three different network layers and their interactions, this project aims to offer a more insightful and integrated approach for transfer management. The main key performance indicators (KPIs), identified in this setting, are transfer and total travel time predictability, delays, probability of missed connections, station and on-board crowding, service robustness, prediction accuracy, reliability and added-value. These KPIs are established for each network level. Data used in the project consists of current and alternative public transport schedules, traveller data from ticketing systems, vehicle location data and pedestrian tracking systems.



4 Results

4.1 Data analytics

This section reports the results of **WP1: Unravelling form and flow dynamics**. This work package aims to understand well the characteristics and evolution of traveller flow dynamics at three different geographical scales, namely hub, urban and regional networks, and their integration, through data analytics. This meets the Goal 1 mentioned above.

T1.1 Big data analytics for travel demand

For the data analytics, **we designed and developed a tool to process, filter and analyse travel demand data**. We specified the data format of the three case studies. In several iterations of the requirements analysis process, the available datasets from the case studies were analysed, and the desired functionalities of the data analysis tool were defined together with all partners. Based on the requirements, the architecture of the tool was designed, and the tool was implemented accordingly. The data storage backend consists of a modern graph database, which contains a transit layer and a passenger layer to store the cleaned and pre-processed input data. Queries against the database are implemented in the Apache Gremlin open source graph query language can be called via a set of well-defined REST APIs. The APIs are defined using Swagger 2.0, which ensures easy documentation and integration into other applications. Besides the main data analysis functionality, the tool also provides administrative features such as user authentication and lower-level data inspection.

T1.2 Multi-level analysis of traveller flows

We also analysed the traveller dynamics that take place at each different level. Descriptive analyses by using big transportation data collected from smart technologies were performed: pedestrian flows inside a single multi-modal transport hub in Switzerland; flow dynamics on an urban public transport network in the Netherlands; and the transit flows in a region of Sweden. A number of different techniques are used and developed for the different scales of analyses. This multi-level analysis is required for understanding flow dynamics of both pedestrians and public transport passengers. We also established a common system representation and mathematical notations to be used throughout the project and modelling developments. Urban form plays a significant role in traveller dynamics and mobility, as topography and human-built infrastructures has a big impact on mode choice of people to move around.

T1.3 Visualizing the evolution of travel flows

The main result of this task is the visualization of travel flows for different relations, aggregation levels and contexts. A graphical analysis tool has been developed to enable the visualization of travel flows at different network layers and analyse how they evolve. A live map displays a range of travel flow characteristics and produce statistics and graphs through a user interface. Some of principles in the tool developed in Task 1.1 have been adopted when introducing the related functionalities. The graphical tool is instrumental for understanding system dynamics, support researchers in scenario design and discussions with stakeholders by conveying current conditions and the implications of alternative scenarios.

The associated deliverables with the aforementioned results are as follows:



1. D1.1: Big travel demand data analytics support tool
2. D1.2: Form and flow dynamics at interchange, urban and regional net-work layers
3. D1.3 Graphical analysis interface of travel demand flows

4.2 Passenger flow measures and modelling

The passenger flow models have been developed in **WP2: Measuring and modelling passenger interchange activities**. This work package achieves the Goal 2 which aims to provide traveller-focused tools for measuring and modelling passenger interchange activities.

T2.1 Passenger-focused indicators of service variability

For analysing passenger flows, we first proposed methodologies for quantifying and measuring service variability in the context of public transportation. To this end, the concepts of reliability and robustness have been introduced, dealing with recurrent disturbances and non-recurrent disruptions. A range of variability measures have been presented, and they allow us to analyse and evaluate passenger flows across entire public transportation networks, with a special emphasis on transferring flows. Indicators were first discussed and developed separately at each level, and then they are combined in an integrated framework. For instance, measures of travel reliability for multi-modal trips were defined that include waiting, in-vehicle and transfer time. Similarly, measures of travel and arrival time predictability as well as the likelihood of missed connections were formulated. The measures have been tested and applied to three different case studies that were considered throughout the project. The wider aim of the development of service variability measurers pertains to the development of a multi-layer passenger flow model that can represent flow dynamics across a public transportation network, and which allows to evaluate and steer transit operations from the perspective of individual passengers.

T2.2 Linking hubs and urban networks and T2.3 Moving between networks

We have developed models used to represent passenger flow dynamics in the public transport system on specific levels. The focus of each model is the following:

- i. **Hub level:** the interaction between passengers and their detailed movements within a transportation hub.
- ii. **Urban level:** the interaction between passengers and vehicles within an urban public transport network operated by one or multiple transport service providers including the passenger flow dynamics.
- iii. **Regional level:** the interaction between primarily passenger trains, but also regional buses, operated by various service providers in a regional/national railway traffic system.

These models have been enhanced and developed further by integrating aspects from the other levels in order to better capture the overall system dynamics, particularly related to connecting services and passenger journeys/transfers that cross the different levels. Originally, we suggested to order the models by geographical scale, from regional to urban to hub. However, when described from the passenger point of view, the interactions among the levels occur in a different order. The hub level is now considered as the intermediate level used by passengers when moving between networks. As a consequence, we use the hub level as an interface between the urban and regional levels.



The associated deliverables with the results of WP2 are as follows:

1. D2.1: Passenger-focused indicators of service variability
2. D2.2: Multi-layer passenger flow network model

4.3 Smart transfer modelling

This section reports the results of **WP3: Methods for planning and operating robust services**. This work package aims to develop innovative methods for planning and operating robust public transport services, including real-time and integrated strategies that involve forecasting passenger behaviour. This achieves the Goal 3 mentioned in Section 2.

T3.1 Real-time traffic management optimization and T3.2 Smart real-time strategies

Towards the real-time management of public transport services, we focused on how to enable an integrated passenger-focused management approach incorporating the models developed within tasks 2.1 and 2.2 and developed efficient management and control strategies. The strategies enable improved coordination and achieve smooth passenger transfers. The work has resulted in a specification of the configuration of each modelled level (hub, urban and regional) and the proposed types of management strategies as well as the required information flow. Figure 2 illustrates the framework of integration. It shows that we assume the hub level as an interface (as defined in WP2) and the required information flows among the different levels.

T3.3 Short-term forecasts of passenger flows

We then developed algorithms for short-term forecasting of passenger demand, which underlie the real-time passenger-oriented strategies, based on the developed models in WPs 1 and 2. The algorithms developed support the refinement of the control strategies of Tasks 3.1 and 3.2 by providing passenger flow prediction from multiple available data sources. At each time step, the (updated) passenger flow is predicted in reaction to the controls executed, and this helps the decision of current and future control strategies. For each of the three different levels of transportation, we have established the specific algorithm for short-term passenger flow prediction.

T3.4 Integrated tool for evaluating strategies

We have also developed an integration tool aiming at performing an integrated analysis of the three different models at hub, urban and regional levels in order to evaluate real-time management strategies for smooth transfers. For the analysis, the models are required to be run in a sequence and to communicate each other with respect to the data exchange. The role of the developed tool, called TransFormInt, is to enable easy definition of the model sequences and control their execution. Also, the tool performs the necessary data transformations of the model outputs into the input data format required by the other models. Three interactions can be defined in the sequence of the tool: 1) urban to hub models, in which the timetable decided in the urban level is provided to the hub level as pedestrian demand, 2) hub to urban models, in which the pedestrian walking time distribution is transferred, and 3) regional to urban models, the revised timetable of regional trains is considered in the urban level. This task originally planned to be done by IBM, but upon their leaving, EPFL took over and performed the tool creation.

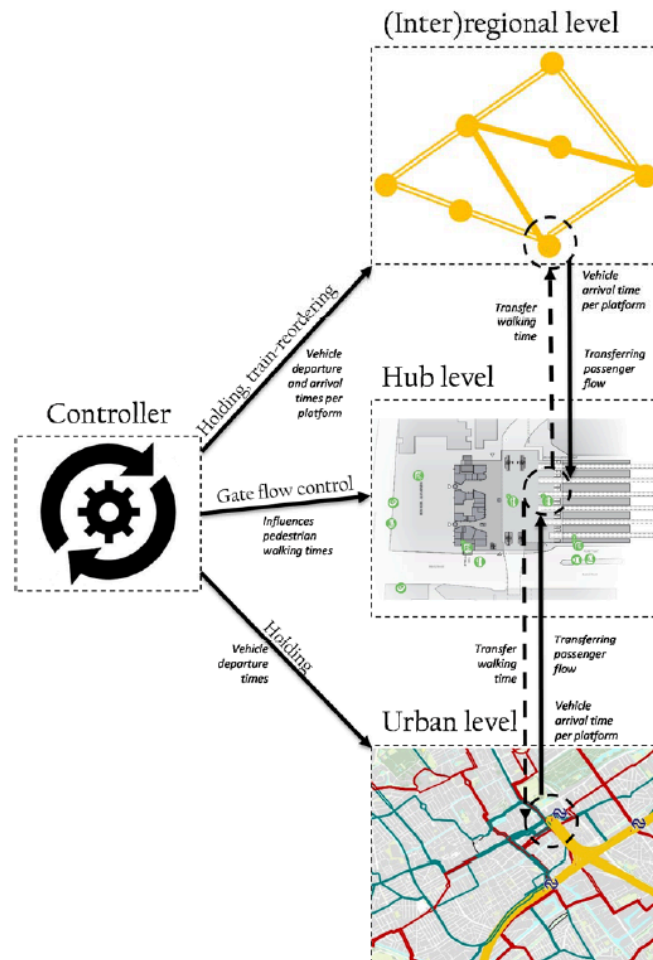


Figure 2: Illustration of the integrated model framework. The interaction between the urban, hub and regional levels occurs primarily via the flow of passengers and their transfers between the (inter)regional and the urban public transport service network.

The associated deliverables with the results of WP3 are as follows:

1. D3.1 A toolbox of real-time strategies for smart transfers
2. D3.2: Algorithms for short-term prediction of passenger flows
3. D3.3: Tool for evaluating real-time strategies

4.4 Smart cities demonstration

Finally, we report the results of case studies, which has been done in **WP4: Application and demonstration of smart transfer strategies**. This work package aims to achieve the Goal 4: develop, apply, demonstrate and evaluate innovative transfer strategies under various scenarios and case studies.



T4.1 Deploy multi-level real-time traffic management strategies and T4.2 Evaluate the impacts of smart transfer schemes under various scenarios

For the application of the developed strategies, we first discussed the set-up of both three local case studies and the joint case study which evaluates the impacts of the smart transfer strategies developed in the previous work packages. We here also operationalized the optimization framework and algorithms developed in WP3. To this end, we first confirmed the required data for the case study, focusing on the interactions among the levels. We defined the scenarios evaluated in the joint case study which includes detailed network representation and model testing.

The development of the multi-layer integration modelling tool calumniated here and it is applied to the flagship case study of The Hague in the Netherlands using a sequence of models: train traffic management model, pedestrian flow model and dynamic public transport assignment model. The models exchange information about vehicle and passenger flows and delays, allowing the modelling of propagation and spill-over effects as well as potential mitigation measures. The results provide confidence that the proposed solutions can provide insightful findings for analyzing the consequences of service disruptions as well as measures to mitigate their impacts. This is the first study to implement and allow the quantification of disruptions while accounting for passenger flow distribution across regional, urban and hub service layers.

Additional case studies at the hub level (the Lausanne station) and regional transit network (Region Blekinge) further assessed the impacts of developed flow control and re-scheduling strategies, respectively.

The associated deliverable is:

1. D4.1 Impacts of smart transfer schemes under various scenarios

5 Collaboration and dissemination

5.1 National cooperation

First of all, IBM withdrew from the project on 31 August 2017 following the departure of Marco Laumanns from IBM. EPFL tried to minimize the impact on the project by taking over some tasks allocated to IBM, but this resulted in losing a part of national cooperation in commercial area. Interactions between EPFL and the Swiss stakeholders ensure national cooperation. The project keeps the website (<http://www.trans-form-project.org/index.php/news/>) updated to disseminate the outcomes of the project to public. As will be mentioned below, EPFL hosted a big workshop at EPFL and had the keynotes including Francesco Corman from ETH Zurich and Gabrio Caimi from SBB/CFF. We also had participants from stakeholders such as SBB/CFF and t-I (Transports publics lausannois). The workshop was very successful and a nice opportunity to share the project outcomes and to interact with participants including possible stakeholders.

5.2 International collaboration

The project has been performed in the collaboration with the international partners, TUD, BTH, LiU, EPFL, IBM and ETRA, under the coordination of TUD. The collaboration improved the quality of works done in the project, and each partner used the specific expertise to perform the project activities. Especially, **the core of this project was the multi-level approach to integrate the real-time**



management strategies of different geographical levels of public transport networks: hub, urban and regional levels. This was impossible to achieve without the collaboration. Specifically, the three levels of modeling and analyses are performed as follows: (1) Hub level – EPFL – Lausanne train station, (2) Urban level – TUD – The Hague urban PT network, (3) Regional level – BTH and LiU – Blekinge regional railway network. Each partner has developed specific models and management strategies as planned, and thanks to that, we could perform the integration of the multi-level models. **The integration across the hub, urban and regional service layers was first performed by this project**, which is a strong contribution both from scientific and practical point of view, since it allowed the quantification of various disruptions in public transport networks while accounting for passenger flow distribution. The partners from industry, ETRA and IBM, supported the project by developing the tools used in the project. The visualization tool developed by ETRA allowed us to easily visualize the results of the developed models and strategies, which were helpful to show the impact of the project. After the withdrawal of IBM, EPFL took over to develop a tool for the model integration. The tool allowed to run the different levels of models in sequences and to smoothly exchange the required information among the models.

Throughout the project, **three types of meetings have taken place to ensure international cooperation**. “Management meetings” have been scheduled monthly. At least, a representative for each institute in the consortium participated to these meetings (conference call using Skype). “Task specific meetings” were also scheduled depending on the on-going actions in each task. Technical details have been discussed among a subgroup of partners. In average, the frequency was twice a month for on-going tasks. This helped in particular the detailed discussion for data format and algorithms for the integration. The last type of meeting is a yearly physical meeting hosted in turn by each partner, which helped us to keep the good communication among the partners, to confirm the project on-track and to discuss the details of the developed models, algorithms and tools, which were difficult to achieve by conference calls. The first meeting was hosted by Delft University of Technology, Delft, The Netherlands, on 03-04/03/2016. The second meeting was hosted by ETRA I+D, Valentia, Spain, on 22-24/03/2017. The third meeting was hosted by Delft University of Technology, The Hague, The Netherlands, on 23-24/10/2017. The fourth was hosted by Blekinge Institute of Technology, Karlskrona, Sweden, on 23-25/05/2018. The fifth was hosted by Linköping University, Stockholm, Sweden, on 18-19/10/2018. The final workshop was hosted by EPFL, Lausanne, Switzerland on 03/04/2019, which was followed by the big workshop on 04/04/2019. We had keynotes and participants from different countries, not only from Switzerland. This will be discussed in more details in the following subsection for dissemination.

5.3 Dissemination

As well as publishing and presenting the project results in international journals and conferences, we have held workshops to disseminate the project activities to stakeholders. Tailored workshops and bi- or multi-lateral interactions and meetings have been organized with the project stakeholders, focusing on the development of the case studies, receiving practical input and sharing intermediate results.

In the project meeting in The Hague, the local HTM implementation partner presented their system, operations and tooling and the flagship case study developments have been discussed with them, as well as network representation and potential scenarios.

In the first year, the main result of this task was the definition of the case studies. For each case study, we described the stakeholder and implementation partners, the input data, the case study aim in terms of management strategies and methodological advances, and the set-up for the modelling phase. These descriptions are also reported in deliverable “D5.1 Case study set-up descriptions”.



In the end of project, the consortium **held a workshop entitled “Managing Passenger Flows in Multi-Modal Public Transport Systems”**, at EPFL on April 4, 2019. EPFL was the host of workshop. The objectives of the workshop were to share the project outcomes with possible stakeholders and to discuss practical challenges and the solutions to public transport systems operation. To this end, we organized the workshop as follows: (a) keynotes both from academia and from industry, (b) presentations of the consortium, (c) an interactive session using poster or displayed presentations. As the keynotes, Francesco Corman from ETH Zurich, Gabrio Caimi from SBB/CFF, and Sandra Nijenstein from HTM gave talks. In total, we had 34 participants from stakeholders including SBB/CFF, t-l (Transports publics lausannois) and Helsinki Region Transport, from consultants and from academia.

6 Discussion

6.1 Impact of the project results

Real-time public transport network management involves several actors and stakeholders, and this project is expected to help such a complex decision-making process. The project delivered a coherent set of concepts, measures and methods to monitor, analyse and manage urban public transport services which will be of direct value to network managers, transport service providers and operators. These measures and methods are expected to improve the analysis of public transport service quality. This, in turn, is expected to help service providers and operators to decide on good measures for increased service reliability, increased travel and transfer time predictability as well as increased information accessibility and information quality.

Not only to the stakeholders, the impact of the project extends to urban problems toward sustainable cities. Public transport offers an effective way to reduce congestion, air pollution, and energy consumption. Congestion is still an important issue in growing cities, and the modal shift by improving public transport services is a solution. Indirectly, this project also has an impact on energy consumption. Although it is difficult to quantify the impact on energy consumption and saving of greenhouse gas emissions, this project can contribute to the analysis necessary for effective investments in order to promote a modal shift towards more energy efficient and environmental sustainable modes by enabling better performing and more attractive public transport systems.

The project involves processing of both video camera data and data from smart ticket systems. Showing how to utilize the data from various recent technologies to understand and analyse the passengers' behaviour could benefit the public transport managers and operators directly. Also, this type of data is very privacy sensitive, and the sharing of data therefore requires through consideration on the level of aggregation and anonymization that need to be handled. For the case study analysis, the data handling implementation, also the anonymized and aggregated data may need to be handled by the local project partner only. However, data processing results, in terms of the developed performance measures, will be possible to share between the partners and between the three modelling levels.

7 Conclusions and outlook

Relying on the availability of various smart data, this project proposed a solution to multi-modal public transport systems. The approach introduced in the project is a real-time coordinated, multi-level integrated and demand-driven approach, which can achieve the better understanding transferring



dynamics and developing strategies to support decision makers for seamless travel experience of travelers. A multi-level approach is adopted for monitoring, analyzing and managing urban dynamics in relation to interchanging flows, in particular focusing on (1) Transport hub network, (2) Urban network and (3) Regional network, with different geographical scales respectively. Based on this integrated framework, the project develops strategies to coordinate inter-modal transfers and deploys short-term predictions of passenger flows. The prediction models consider and reflect the uncertainty in the systems and allow us to assess the total welfare of coordinating transfers by considering the measures of passenger activities.

Four main work packages have been performed to achieve the project goals: respectively (i) data analytics for better understanding the characteristics of traveler flow dynamics, (ii) passenger flow measures and modelling to provide traveler focused tools, (iii) smart transfer modelling for planning and operating robust public transport services, and (iv) smart cities demonstration to show and evaluate the impact of innovative transfer strategies. Throughout the project, various methodologies in different fields have been proposed and combined.

The key contribution of the project is the above-mentioned multi-level multi-modal integration. The frequent and solid cooperation among the international partners enabled this approach. Different countries of partners developed different scales of models, algorithms and strategies using their own expertise and specific data, and the effort has been finally integrated in a joint case study. The tools developed in the project also supported the integration approach.

Overall, the project has been well-coordinated and has achieved the defined goals. We will investigate the possibilities for further collaboration, and in particular, hub-urban fixed point problem, transfer flow dynamics pattern analysis using machine learning techniques, more detailed case studies showing the impact of developed strategies with various disruption or uncertainty are possible future works of the project.



8 Publications

8.1 Conference Presentations

Below is a list of presentations given by the researchers from EPFL. For each presentation, the venue/conference name, presenter and presentation title and location are given.

1. 8h Symposium of the European Association for Research in Transportation, Molyneaux, N. (September 2019). The benefits of preventing pedestrian counterflow. Budapest University of Technology and Economics, Hungary.
2. 10th Triennial Symposium on Transportation Analysis (TRISTAN X) Molyneaux, N. (20 June 2019). Improving pedestrian dynamic by preventing counter flow. Hamilton Island, Australia.
3. 19th Swiss Transport Research Conference (STRC), Molyneaux, N. (15-17 May 2019). The impact on pedestrian walking times of counter flow. Ascona, Switzerland.
4. 7th Symposium of the European Association for Research in Transportation, Molyneaux, N. (5 September 2018). Gating as a management strategy for controlling pedestrian flows. National Technical University of Athens, Greece.
5. International Conference on Operations Research, Molyneaux, N. (12-14 September 2018). Reducing variability in passenger walking times with two management strategies inside transportation hubs. Université libre de Bruxelles, Belgium.
6. 7th International Symposium on Dynamic Traffic Assignment: Smart Transportation, Molyneaux, N. (6-8 June 2018). Controlling pedestrian flows using a dynamic traffic management system. The University of Hong Kong, Hong Kong.
7. 18th Swiss Transport Research Conference (STRC), Jeanbart, C. (16-18 May 2018). Multi-objective optimization of moving walkway networks in transportation hubs. Ascona, Switzerland.
8. 18th Swiss Transport Research Conference (STRC), Molyneaux, N. (16-18 May 2018). Two management strategies for improving passenger transfer experience in train stations. Ascona, Switzerland.
9. 17th Swiss Transport Research Conference (STRC), Molyneaux, N. (17-19 May 2017). Pedestrian management strategies for improving flow dynamics in transportation hubs. Ascona, Switzerland.

8.2 Published works

This subsection lists publication from EPFL. The list includes published articles (journals papers, proceedings and book chapters), as well as future expected publication (listed separately).

1. Molyneaux, N., Scarinci, R., and Bierlaire M. (2019) Improving pedestrian dynamic by preventing counter flow. Proceedings of the 10th Triennial Symposium on Transportation Analysis (TRISTAN X), 17-21 June 2019. Peer-reviewed.
2. Molyneaux, N., Scarinci, R., and Bierlaire M. (2019). The impact on pedestrian walking times of counter flow. Proceedings of the 19th Swiss Transport Research Conference (STRC), 15-17 May 2019, Ascona, Switzerland.



3. Molyneaux, N., Scarinci, R., and Bierlaire M. (2018) Controlling Pedestrian Flows Using a Dynamic Traffic Management System. Proceedings of the 7th International Symposium on Dynamic Traffic Assignment: Smart Transportation, 6-8 June 2018. Peer-reviewed.

Future expected publication:

4. Molyneaux, N., Scarinci, R., and Bierlaire M. Tentative title: Design and analysis of control strategies for pedestrian flows. To be submitted to a peer-reviewed journal during summer 2019.

The articles and published deliverables by the other project partners are listed in the deliverable: “D5.3 Articles submitted to scientific journals”.



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10 Appendix

10.1 List of deliverables

Below is a list of project deliverables attached to this report as appendices:

1. D1.1: Big travel demand data analytics support tool
2. D1.2: Form and flow dynamics at interchange, urban and regional net-work layers
3. D1.3 Graphical analysis interface of travel demand flows
4. D2.1: Passenger-focused indicators of service variability
5. D2.2: Multi-layer passenger flow network model
6. D3.1 A toolbox of real-time strategies for smart transfers
7. D3.2: Algorithms for short-term prediction of passenger flows
8. D3.3: Tool for evaluating real-time strategies
9. D4.1 Impacts of smart transfer schemes under various scenarios
10. D5.1 Case study set-up descriptions
11. D5.2 Exploitation and commercialization
12. D5.3 Articles submitted to scientific journals