Flexible Integrated Transport Systems' Potential to Unleash Net Benefits in Rural Areas

Florian Heinitz

Abstract This contribution presents a flexible integrated transport system which features the combination of anticipated peer-to-peer ridesharing and state-licensed on-demand services, complementing fixed-line scheduled transit. A sequential method of estimating the demand potential of such a collaborative service structure versus its supply side is formalized and studied by simulating synthetic network models. The workflow is set to support planning, to prove the efficiency of integrated solutions, and to reduce uncertainties for market entrants.

Keywords Flexible integrated transport system · Ridesharing · Mobility on demand · Mobility as a service · Demand-responsive transport · Demand model

1 Introduction

1.1 Context and Problem Statement

Germany, among other countries, is about to modernize its passenger transportation legislation [1]. Even though thought leaders are already pressing ahead with scenarios of an extensive replacement of individual car traffic by optimized self-driving pooling-capable fleets and strengthened transit, a coexistence will remain on the agenda for a number of years to come [2]. Thus, compact forecasting instruments for a mixed operation are needed. The benefit-cost relationship of incremental demand-responsive transport (DRT) offerings shall be assessed against the backdrop of fixed-line scheduled (FLS) transit. The definition of standards to be met by the new services themselves has not been clarified yet, but will affect the attractivity for market entrants.

The intended and optimized complementarity of DRT with existing FLS in rural/suburban operation areas could be realized by further developing traditional

F. Heinitz (✉)
Erfurt University of Applied Sciences, Altonaer Strasse 25, 99085 Erfurt, Germany
e-mail: heinitz@fh-erfurt.de

C. Ha-Minh et al., (eds.), *CIGOS 2021, Emerging Technologies and Applications for Green Infrastructure*, Lecture Notes in Civil Engineering 203,
https://doi.org/10.1007/978-981-16-7160-9_164

line networks of public transport to flexible integrated transport systems (FITS), as demonstrated, for example, by Mounce et al. [3]. Timetable-free ride pooling could go beyond a mere feeder function to transit hubs [4, 5], allowing for an overall welfare gain by more frequent and transfer-free routings.

In the course of the transformation envisaged, the identification of common methodological principles and database platforms to overcome the dichotomies between traditional scheduled and new peer-to-peer matching-based services as well as between individual mobility and "mass transit" concepts turns out to be a non-trivial task—not to mention the overcoming of operation pattern, planning IT and appraisal practices.

With investigations in realistic dimensions denied so far, market entries and concession rights tenders in the blind bear considerable financial risk and tend to be smaller in doubt than necessary to achieve critical mass. Rural areas reveal this set of problems to a particularly high degree [6–8]. Service goals cannot possibly be met with conventional FLS bus operations. At the same time, large fleets of passenger cars, mostly in solo use, dominate the road traffic. At least a single-percentage proportion could well be matched and incentivized to carry passengers. If transport authorities knew the actual residuals at specific times and origin-destination pairs, the supplementary demand-driven offers would therefore only have to be designed for a significantly lower transport demand and would thus require fewer funds. But how can these be derived?

1.2 Research Objectives and Paper Overview

The objective is to explore welfare-increasing, incremental public DRT schemes in connection with anticipated ridesharing, to be incentivized in greater measure. The study aims at a practically manageable, standardized method for the systematic estimation of the additionally addressed demand by dynamic (peer-to-peer and institutional) ride matching in a respective fulfillment time window [9]. Based on this, resulting system-wide effects for further evaluation [10, 11] of investments, the justification of possible additional public expenditure, and the expected intensity of competition in the event of a private-sector realization of such offers have to be investigated. The way of interlacing the range of heterogeneous services is neither self-evident nor trivial to model, bearing in mind that the response to a stochastic demand will be a stochastic operation pattern. Instead of using average values in the classic 4 step algorithm [12], the computational results and indicators that are key to the economic appraisal derived from them are to be treated as variates. Questions of particular interest comprise the actual bundling capability across transport mode boundaries, the resulting demand residuals, the dependency of the gain in mobility and positive environmental effects on subsidization and a possible constraining of a FLS trunk network.

The remaining article is structured as follows: The proposed FITS planning approach is presented in Sect. 2—comprising the introduction of the workflow (2.1) and its formal description (2.2). The paper continues with the implementation and data requirements in Sect. 3, followed by a discussion and conclusions.

2 Sequential Approach to FITS Planning

2.1 Modeling Idea and Workflow Outline

The tasks described above suggest a new multi-level model of the regional transport supply-demand interaction, integrating private and public transport beyond the established concepts of intermodality, park-and-ride, etc. The advanced model sequentially draws on the proven components of the traditional 4 Step Algorithm, being compartmentalized by the aspects of trip generation/distribution/modal choice/routing.

The key indicator is the adoption rate of the residual, unsatisfied public transport demand and the resulting users' willingness to pay for filling the service gaps—for practical usefulness differentiated by origin-destination pairs and desired departure times. In the light of the still-existing legal divide of passenger carriage, the contributions (i) of the incentive system-dependent private individual car traffic ("anyway transports") by casual, dynamic or long-term ridesharing (RSH) and (ii) the dedicated-fleet DRT operations are to be distinguished in principle. As depicted and detailed in Figs. 1 and 2, the different offerings and corresponding demand segments are sequenced—to stepwise diminish residual demand. Conceptually, the decision tree should be in accordance with the respective achievable minimum of the generalized user costs which are assumed to be the decisive criterion. The segmentation proceeds as follows: The total demand is subdivided into (self-servicing) a priori car users and the initial residual (R#0) of potential (elective and captive) public transport users, subject to feasibility. This residual is primarily directed to the (already massively subsidized) FLS network, but cannot be addressed entirely, thus resulting

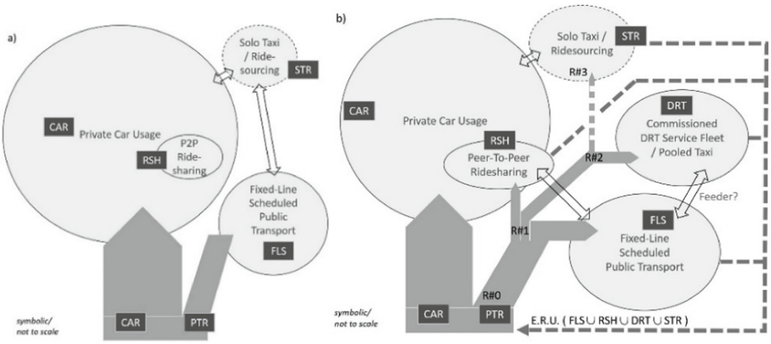

Fig. 1 Comparison of classic passenger transport choice procedure (**a**) and proposed FITS (**b**)

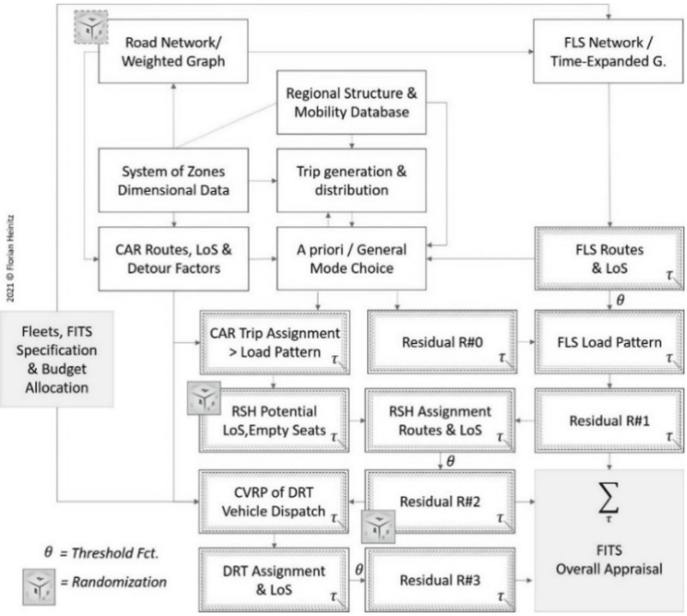

Fig. 2 Workflow of the FITS planning model and test environment

in the first residual (R#1). This is the demand the segment ridesharing (RSH) has to deal with up to a certain proportion, leaving the second residual (R#2) behind. This provides the quantity structure for public DRT offerings. Taking into account its limitations, too, the difference is referred to as third residual (R#3). This trip demand can finally be met by private solo taxis or ridesourcing (STR).

The role of the model is to experimentally obtain expected values of demand and cost.

Any model run is parameterized by the existing or synthetic road network graph, existing or synthetic FLS timetables, furthermore the regional structure, household motorization and mobility database, the reservoir of DRT vehicles, and total public transport budgets.

2.2 Formal Description

Table 1 itemizes the model variables used. The dimensions of the model are the following: The demand side is stepwise segmented into "CAR", "PTR", "FLS", "RSH", "DRT", and "STR". The transport geographic conditions are represented by physical graphs for infrastructure and virtual graph for timetabling. First mentioned consist of sets of nodes $\{i\}$, with subset for settlement locations, that are establishing

Table 1 Model variables and parameters—key to symbols

$\left\{T_{ij,\tau}^{(..)}\right\}$ demand in number of trips	P, P_{min} choice probability, de minimis ~
$a_{i,\tau}^{(CAR)}$ share of private car availability	T_{min} minimum demand threshold
$g_{ij,\tau}^{(\pi)}$ frequency distribution of π	$\mathbf{L}_{ij,\tau}^{(FLS)}$ level of service (LoS) vector *FLS* etc
$K_{ij,\tau}^{(RES)}$ total residual seating capacity	$\overline{\mathbf{L}}_{ij,\tau}^{(FLS)}$ minimum accepted LoS for *FLS*
$p_{ij,\tau}^{(RSH)}$ unit price of supplied *RSH*	$\overline{\mathbf{L}}_{ij,\tau}^{(DRT)}$ minimum targeted LoS for *DRT*
$t_{ij,\tau}^{(DIR)}$ direct travel time	$\delta_{ij,\tau,e}^{(CAR)}$ optimal path-network assignment
$c_{ij,v}^{(VEH)}$ effective unit cost f. private car	$\mathbf{R}_{v,\tau}^{(...)} = \left\{i_{v,\tau}^{(...)}\right\}$ routing of DRT vehicles
$c_{ij,f}^{(VEH)}$ unit vehicle operation cost *DRT*	$V_{i,\tau}^{(CAR)}$, $V_{i,\tau}^{(FLS)}$ systematic utilities of *CAR*, *FLS*
γ_{ij}(Z) detour factor to serve requests Z	$\boldsymbol{\beta}^{(...)} = \left\{\beta_h^{(...)}\right\}$ vector of functional parameters

a system of zones as trip origins and destinations, vehicle locations O, to be origin-destination paired as $\{ij\}$; and a set of edges E $= \{e\} = \{(i, j)\}$. The time domain is structured into day times and respective departure time windows $\{\tau\}$. The entirety of trips is segmented by trip party size $\pi = \{1, 2, 3, \ldots\}$. Moreover, a set of private cars V $= \{v\}$ of seating capacities K_v and location $O_{v,\tau}$ prior to τ is assumed, along with a fleet of commissioned DRT service vehicles F $= \{f\}$ of seating capacity K_f and location $O_{f,\tau}$ prior to τ. The following balance Eqs. (1–7) interlink the demand segments: The initial residual R#0 of all potential (captive and elective) public transport users is obtained by

$$T_{ij,\tau}^{(R\#0)} = T_{ij,\tau}^{(PTR)} = T_{ij,\tau} \cdot \left(1 - a_{i,\tau}^{(CAR)}\left(1 - \sum_{\pi} g_{ij,\tau}^{(\pi)} \cdot P_{ij,\tau}^{(FLS)}(\pi)\right)\right) \tag{1}$$

with

$$P_{ij,\tau,v}^{(FLS)} = P\left(t_{ij,\tau}^{(DIR)}, \frac{c_{ij,v}^{(VEH)}}{\pi}, p_{ij,\tau}^{(FLS)}, L_{ij,\tau}^{(FLS)}\right) \tag{2}$$

describing the principal mode choice functions. These functions are of the binary logit type with a choice set $\{CAR, FLS\}$ taken as a basis, thus omitting the other mobility options at this point in time. The two systematic utility functions are of linear forms.

$$P_{ij,\tau,v}^{(FLS)} = \frac{\exp\left(V_{i,\tau}^{(FLS)}\right)}{\exp\left(V_{i,\tau}^{(FLS)}\right) + \exp\left(V_{i,\tau}^{(CAR)}\right)} \text{ with} \tag{3}$$

$$V_{i,\tau}^{(CAR)} = \beta_0^{(CAR)} + \beta_1^{(CAR)} t_{ij,\tau}^{(DIR)} + \beta_2^{(CAR)} \frac{c_{ij,v}^{(VEH)}}{\pi} \tag{4}$$

$$V_{i,\tau}^{(FLS)} = \beta_0^{(FLS)} + \beta_1^{(FLS)} p_{ij,\tau}^{(FLS)} + \left\langle \beta^{(FLS)}, L_{ij,\tau}^{(FLS)} \right\rangle \tag{5}$$

A differentiation by trip party size π proved to be meaningful. Insufficient service level of the FLS system constitutes the first residual R#1:

$$T_{ij,\tau}^{(R\#1)} = T_{ij,\tau}^{(PTR)} - T_{ij,\tau}^{(FLS)} = T_{ij,\tau}^{(PTR)} \cdot \theta\left(L_{ij,\tau}^{(FLS)} - \overline{L}_{ij,\tau}^{(FLS)}\right) \tag{6}$$

The actual RSH demand is a linear combination of discriminated cases for k passengers

$$T_{ij,\tau}^{(RSH)} = T_{ij,\tau}^{(R\#1)} \cdot \sum_{v(ij,\tau)} \sum_{k} k \cdot \theta\left(P_{ij,\tau,v}^{(RSH)}(k) - P_{min}\right) \cdot P_{ij,\tau,v}^{(RSH)}(k) \tag{7}$$

with respective choice probabilities for k out of $\mathrm{K}^{(RES)}$ available seats (Fig. 3).

$$P_{ij,\tau,v}^{(RSH)}(k) = P\left(k, K_v^{(RES)}, t_{ij,\tau}^{(DIR)}, p^{(RSH)}/c_{ij,v}^{(VEH)}(k), \gamma_{ij}(\mathrm{Z}_k), \varphi\right). \tag{8}$$

$\gamma_{ij}(\mathrm{Z})$ denotes the detour factor for OD-Pair ij according to $\{\delta_{ij,\tau,e}^{(CAR)}\}$ to cater for requests—as r-ary set of O-D pairs $\mathrm{Z}_k := \left\{\left(i', j', \pi'\right)_r\right\}$ with $\sum_r \pi_r' = k$.

By diminishing R#1 by the demand that can be covered through RSH, one obtains R#2:

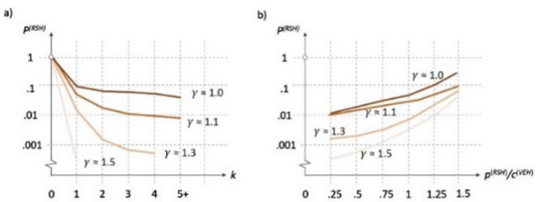

Fig. 3 Exemplary base cases of principal dependencies of $P^{(\mathrm{RSH})}$ **a** monotonously decreasing by k number of additional passengers taken versus detour factor γ, **b** by price incentive relative to operating cost versus detour factor γ

$$T_{ij,\tau}^{(R\#2)} = T_{ij,\tau}^{(PTR)} - T_{ij,\tau}^{(FLS)} - T_{ij,\tau}^{(RSH)} = T_{ij,\tau}^{(PTR)} \cdot \left(1 - P_{ij,\tau,v}^{(FLS)}\right) - T_{ij,\tau}^{(RSH)} \tag{9}$$

With a randomized quantity structure on the basis of the results (9), (capacitated) multiple vehicle routing problems of a fleet $\{v\}$ positioned at $\{O_{v,\tau}\}$ need to be solved stepwise for the time windows τ considered. Depending on the prior FITS specification, the routing $R_{v,\tau}^{(\ldots)}$ considers de-minimis thresholds T_{min} as well as optional split pick-ups. The third residual R#3 accumulates the demand in case $\overline{L}_{ij,\tau}^{(DRT)}$ cannot be met:

$$T_{ij,\tau}^{(R\#3)} = T_{ij,\tau}^{(R\#2)} - T_{ij,\tau}^{(DRT)} \cdot \theta\left(T_{ij,\tau}^{(R\#2)} - T_{\min}\right) \cdot \theta\left(L_{ij,\tau}^{(DRT)} - \overline{L}_{ij,\tau}^{(DRT)}\right). \tag{10}$$

(θ is the classic step function, applied to scalar quantities and to elements of vectors.)

3 Preliminary Implementation

With a comprehensive empirical foundation of the built-in choice models still pending, a prototype, coded within a *Java* framework, was first created for study purposes of the entire workflow before the transfer to existing large transport models and the translation into a *PTV VISUM* procedure sequence. Due to the small model size at first and the decomposition into subproblems, the combinatorial complexity is deemed manageable.

The model instance's characteristic is given in brief: An area of roughly five thousand inhabitants, owning 2600 private cars is considered. There are four types-of-operating days—working day outside (ST) or during (FW) of the school holidays, Saturday (SA), Sunday/Public Holiday (SF). Just ten traffic cells and a road network of 36 bidirectional links, forming with a coarse grid corresponding to the territorial structure, were modeled. The travel times are marginally randomized. In addition, free-flow conditions are assumed. For the types-of-day, 34/28/19 and 17 time windows, irregularly distributed throughout 24 h, are distinguished. The investigation area is assumed to be served by four FLS lines with realistically differentiated timetables across the types-of-operating days (Fig. 4). The mesoscopic demand by household type and public transport affinity groups in terms of trip rates broken down by purposes, party sizes, and choice captivity, was generated on the basis of the *MiD* 2017 national household travel survey data set for the respective area type [13]. Assuming a certain frequency distribution of vehicle fleets and their seating capacities for each household type in combination with car trip party sizes and assigned paths $\delta_{ij,\tau,e}^{(CAR)}$, the count of unoccupied seats $K_{ij,\tau}^{(RES)}$ for each triple (i, j, τ), or pair (e, τ) respectively, could be established.

The model reproduces the basic effects as expected. The question of the DRT potential (R#2) can only be answered illustratively, since the ridesharing adoption rates may only be estimated vaguely at this point. The supply side evaluation yields helpful empirical results. For example, the percentage of bundleable O-D pairs by the

Table 2 Indicators of test model instance, by type of weekday

Type-of-day	ST	FW	SA	SF
Area total trip count	16.5k	14.9k	12.3k	8.3k
Mean modal share of FLS %	6.1	3.2	1.9	0.6
Mean share of residual R#1 versus Total Trips %	2.7	2.9	3.2	3.3
Average ratio empty car seat/trip	2.93	3.00	2.89	2.28
Range of unweighted average ratios empty seats/residual demand R#1 (>0), for all O-D pairs, across time windows	0.16–109.1	1.47–15.8	3.7–15.3	1.1–48.3
Count rides requested at $T_{\min} = 1(=3)$	427 (281)	368 (251)	182 (64)	158 (43)
Distinct O-D pairs requested $T^{\min} = 1(=3)$	50 (19)	49 (18)	59 (9)	61 (7)

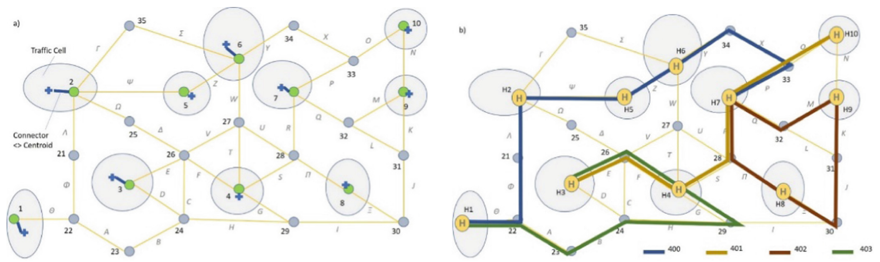

Fig. 4. Instance's system of zones w/road network (**a**) fixed-line scheduled services (**b**)

same car trip can be increased from 1.3 for no or minor detours to 6.1 to a maximum detour factor $\gamma_{ij} = 1.7$. Table 2 exhibits some of the quantitative analysis options created and points on the challenges, particularly the many O-D pair that may need to be covered in the case of $T_{\min} = 1$. Operators ought to be cautious with their level of service guarantees. Further indicators such as DRT vehicle capacity requirements can be derived. Theoretically, with average probabilities of ridesharing occurring assumed to be three percent of the requests, there is at least a noticeable reduction in the demand to be met by DRT.

4 Summary and Conclusions

This piece contributes to efforts to explore scenarios of a reduced solo car use by improving the integration of alternatives. A potentially novel modeling approach to quantitative analyses of flexible integrated transport systems (FITS) was presented in due briefness. This is a proposal to coherently bridge the gap between so far compartmentalized models for the classic transport modes and encourage similar developments in practice. The distinguishing feature is the anticipation of peer-to-peer "anyway" car trip bundling prior to covering the demand intangible by FLS and RSH by DRT. Already the small test application indicates that the purposeful approval of ridesharing significantly simplifies the task of transport provision and lowers resulting cost barriers. The seating capacity of "anyway" car trips clearly outweighs the capabilities of DRT fleets.

A seamless intermodal workflow between different service models was established—sorted by rising incremental costs. First the fixed-cost-based scheduled bus system is to be utilized to the acceptance limit of its level of service, while alternative services progressively seek to address the remainder. Understandably, the chosen sequence does not necessarily have to be in this order. How do customers decide in reality? To what extent are the forms of service substitutive? Clearly, an assessment requires further standardization. Tests were performed for an exemplary small study area. Based on it, cost and vehicle demand estimates, operational limitations and welfare effects from time savings can be derived. The incentivization and surpluses through introduction of a pricing coordinate as well as a back coupling to the households' mobility pattern and the supply side had to be initially left out due to a lack of empirical data. If a corresponding effort is accepted, the modeling is enabled to track the future developments towards FITS and could then be included in regular planning.

References

1. Bundesrat: Gesetzentwurf der Bundesregierung - Entwurf eines Gesetzes zur Modernisierung des Personenbefoerderungsrechts. Drucksache 28/21, Berlin (2021). https://www.bundesrat.de/SharedDocs/drucksachen/2021/0001-0100/28-21.pdf - 21/03/04
2. Ruter AS: The Oslo Study – How Autonomous Cars May Change Transport in Cities, Oslo (2019).
3. Mounce, R.; Wright, S.; Emele, D.C.; Zeng, C.; Nelson, J.D.: A tool to aid redesign of flexible transport services to increase efficiency in rural transport service provision, J. of Intelligent Transportation Systems, 22(2), 175–185 (2018).
4. Minett, P.: Flexible Carpooling to Transit Stations. Final Report - Transit IDEA Program. TRB National Research Council, Washington D.C. (2013).
5. Nabti, J. et al.: Mobility on Demand (MOD) Sandbox Demonstration: BART Integrated Carpool to Transit Access Program. FTA Research report 0155, Washington (2020).
6. Eckhardt, J.; Nykänena, L.; Aapaojaa, A.; Niemib P.: MaaS in rural areas - case Finland. Research in Transportation Business and Management 27, 75–83 (2018).
7. Maretic, B.; Abramovic, B.: Integrated Passenger Transport System in Rural Areas - A Literature Review. Promet – Traffic & Transportation, 32(6), 863–873 (2020).
8. Heinitz, F., Schaefer, M.D.: Current Options and Limitations Implementing Demand-Responsive Public Transport in a Rural County. Proc. 19th ICTS, pp.112–120. Portoroz (2020).
9. Herbawi & Weber 2018 The ridematching problem with time windows in dynamic ride-sharing. WCCI IEEE World Congress on Computational Intelligence, Brisbane (2012).
10. Roukouni, A. Correia, G.: Evaluation Methods for the Impacts of Shared Mobility: Classification and Critical Review. Sustainability 12(24):10504 (2020).
11. Wilkes, G.; Briem, L.; Heilig, M. et al.: Identifying service provider and transport system related effects of different ridesourcing service schemes through simulation within the travel demand model mobiTopp. 2nd Intl. Conf. on Mobility as a Service, Tampere (2019).

12. Ortuzar, J.d.D.; Willumsen, L.G.: Modeling Transport. 4th ed., Wiley (2011).
13. Nobis, C.; Kuhnimhof, T.: Mobilität in Deutschland – MiD Ergebnisbericht, Bonn (2019).