CIRRELT

Centre interuniversitaire de recherche sur les réseaux d'entreprise, la logistique et le transport

Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation

A Proposal for the Evaluation of Demand-Adaptive Transit Systems

Teodor Gabriel Crainic
Fausto Errico
Federico Malucelli
Maddalena Nonato

December 2008

CIRRELT-2008-56

Bureaux de Montréal :
Université de Montréal
C.P. 6128, succ. Centre-ville
Montréal (Québec)
Canada H3C 3J7
Téléphone : 514 343-7575
Télécopie : 514 343-7121

Bureaux de Québec :
Université Laval
Pavillon Palasis-Prince, local 2642
Québec (Québec)
Canada G1K 7P4
Téléphone : 418 656-2073
Télécopie : 418 656-2624

www.cirrelt.ca

A Proposal for the Evaluation of Demand-Adaptive Transit Systems

Teodor Gabriel Crainic[1,2,*], Fausto Errico[1,3], Federico Malucelli[3], Maddalena Nonato[4]

[1] Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT)

[2] Department of Management and Technology, Université du Québec à Montréal, C.P. 8888, succursale Centre-ville, Montréal, Canada H3C 3P8

[3] Politecnico di Milano, DEI, Piazza Leonardo da Vinci, Milano, Italy, 20133

[4] University of Ferrara, via Saragat 1, Ferrara 44100, Italy

Abstract. Demand-adaptive transit systems (DAS) display features of both traditional fixed-line bus services and purely on-demand systems, that is, they offer demand-responsive services within the framework of traditional scheduled bus transportation. Similarly to most transportation systems dedicated to serve several demands with the same vehicle, demand-adaptive transit systems involve a complex set of planning activities made up of many interrelated decisions. The main steps and goals of the planning activities are the same for traditional and demand-adaptive transit systems. Yet, the particularities of DAS services make for a different planning process and require the development of new methodologies. This differentiation also impacts the evaluation processes of DAS lines, either as stand-alone systems or as part of broader city-wide planning activities. The goal of this paper is to identify these differences, describe their impact on evaluation and planning processes, and provide a framework for the evaluation of DAS lines.

Keywords. Public transit, demand-responsive systems, demand-adaptive systems, planning, evaluation.

Acknowledgements. Partial funding for this research was provided by Natural Sciences and Engineering Research Council of Canada (NSERC) through its Industrial Research Chair and Discovery Grant programs, the partners of the Chair, CN, RONA, Couche-Tard, the ministère des Transports du Québec (MTQ), and the Fonds québécois de recherche sur la nature et les technologies (FQRNT) through its Team Project grant program. This research was also partially funded by Regione Lombardia, Italy, through its INGENIO grants.

---

* Corresponding author: Teodor-Gabriel.Crainic@cirrelt.ca

Dépôt légal – Bibliothèque nationale du Québec,
Bibliothèque nationale du Canada, 2008

1 INTRODUCTION

Traditional transit services are particularly suited to handle situations where the demand for transportation is *strong*, i.e., when there is a consistently high demand over the territory and for the time period considered. The high degree of resource sharing by a large number of passengers makes it possible then to provide efficiently and economically high quality, i.e., frequent services operating generally high-capacity vehicles over fixed routes and schedules. Routes and schedules may and do vary during the day, but, in almost all cases, they are not dynamically adjusted to the fluctuations of demand. In contrast, when the demand for transportation is *weak*, e.g., during out of rush-hour periods or in low-population density zones, operating a good-quality traditional transit system is costly. In particular, the fixed structure of traditional transit services cannot economically and adequately respond to significant variations in demand.

Demand-responsive systems are a family of mass transportation services, which are *responsive* to the actual demand for transportation in a specific time period. Such services evolve toward a personalization of mass services: itineraries, schedules, and stop locations are variable and determined according to the needs for transportation as they change in time. Demand-responsive systems were introduced under the name of *Dial-a-Ride* (*DAR*) as door-to-door services for users with particular needs or reduced mobility, such as handicapped and elderly people [11, 15]. The *flexibility* of DAR systems to respond to varying individual requests for transportation provides the means to offer more personalized services, while still maintaining a certain degree of resource sharing. This has lead certain transportation or city authorities to extend DAR services to more general transportation settings.

DAR systems display, however, a number of drawbacks, some of which follow from the extreme flexibility inherent in the system definition. Thus, for example, because the supply of transportation services changes according to the needs expressed for particular time periods, neither the transit operator nor the users can predict the vehicle itineraries, stop locations, and associated schedules. As a consequence, users are obliged to book the service well in advance of the actual desired time of utilization and the actual pick up time is very much left to the discretion of the operator. For similar reasons, it is extremely difficult to integrate DAR and other traditional transit services.

A new type of demand-responsive systems, denoted *Demand-Adaptive System* (*DAS*) has been introduced to address some of these issues [13, 14]. DASs are transit services displaying features of both traditional fixed-line bus service and purely on-demand systems such as DAR. In other words, a DAS attempts to offer demand-responsive services within the framework of traditional scheduled bus transportation. A DAS bus line provides a traditional transit-line service, i.e., without advance reservations, by servicing a given a set of *compulsory* stops, according to a predefined schedule specifying the time window associated with each. On the other hand, similarly to DAR services, passengers may issue requests for transportation between two desired, *optional* stops (not necessarily on the same line), which induces detours in the vehicle routes. The relevance of this kind of hybrid services to general public transit is underlined in [9, 10].

Similarly to most transportation systems dedicated to serve several demands with the same vehicle, demand-adaptive transit systems involve a complex set of planning activities made up of many interrelated decisions. The main steps and goals of the planning activities are the same for traditional and demand-adaptive transit systems. Yet, the particularities of DAS services, combining characteristics of traditional and on-demand systems, make for a different planning process and require the development of new methodologies. This differentiation marks also significantly the evaluation processes of DAS lines, either as stand-alone systems or as part of broader city-wide planning activities integrating private (cars, mostly) and public traffic (as well as, eventually, freight movements).

The goal of this paper is to identify these differences and describe their impact on evaluation and planning processes. We also provide a framework for the evaluation of DAS lines.

The paper is organized as follows. We briefly recall the DAS description in Section 2. Related planning and evaluation issues, together with commonalities and differences among DAS, DAR, and traditional transit services, are discussed in Section 3. Section 4 is dedicated to the description of the proposed methodological framework for the evaluation of DAS services. We conclude in Section 5.

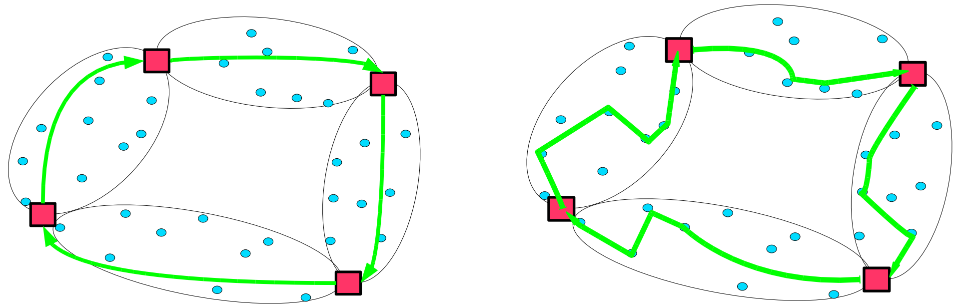
2 DEMAND ADAPTIVE TRANSIT SYSTEMS

Demand Adaptive Systems were first introduced in [13] and addressed in a more general context in [6] (see also [4, 5, 12]). A similar type of service is also described in [14].

A DAS targets low-density/volume demand areas and attempts to conjugate the advantages of traditional transit transportation services and the flexibility of on-demand personalized services. It is based on the observation that even in such areas, there are locations where a relatively important demand may be consistently found: railway and underground stations, shopping centers, hospitals, etc. This provides the possibility to economically design a backbone transit service covering these attractive stops, while allowing vehicles to detour as needed to pick up and drop off passengers at other stops. The latter capability, combined to an on-line request booking system, increases customer satisfaction and the dimension of the potential user group.

In its most general form, a DAS is made up of several lines and is connected to the lines of the traditional transit system. Several vehicles operate on each DAS line providing service among a sequence of *compulsory* stops. Each compulsory stop is served within a predefined *time window*. The collection of time windows corresponding to the compulsory stops, including the start and end of the line, makes up the *master schedule* of the DAS line. This makes up the traditional part of a DAS. Additional service and flexibility is provided by allowing customers to request service from and to *optional* stops, that is, stops which are served only if a request is issued and is accepted. To serve optional stops, the vehicle must generally deviate from the shortest path joining two successive compulsory stops. The set of optional stops that it is possible to visit between two consecutive compulsory stops is part of the design of the DAS line and is denoted *segment*. An optional stop cannot belong to more than one segment. Figure 1(a) depicts the basic DAS service of the compulsory stops, while Figure 1(b) illustrates the same DAS line when user requests for optional stops are present.

Transfers between DAS lines and between these and regular transit lines take place at compulsory stops. Time windows play an important role in this context because they establish time relations among DAS and traditional lines sharing the same compulsory stops. The



(a) Serving compulsory stops (b) serving optional stops

Figure 1: A DAS Line

time windows in the master schedule also influence the flexibility the service may provide for user requests at optional stops. The wider they are, the more flexibility there is. Yet, one cannot increase their width arbitrarily, because the service would then slow down excessively, loosing attractiveness. Notice finally, that the time windows and the specification of segments provide an *a priori* guarantee relative to the longest time users might have to spend traveling on the line.

A DAS service, called MAST, is currently operated in the Los Angeles County as a nighttime service [14]). The system differs slightly from the DAS definition: instead of considering a set of optional stops, it defines a *service area* and provides service among any points in this area. The very regular road network characterizing the area facilitates such a service, the line covering the quasi-rectangular area with a single vehicle traveling back and forth. The service may be assimilated to a circular DAS line with 5 segments. Another implementation of a DAS service is the one we are currently studying for the city of Brescia, in northern Italy. The line links some of the suburbs, mainly mountainous regions, to the center of the city. The contemplated DAS line consists of 6 segments and a total of 53 optional stops. We are currently studying possible designs and simulating the operations.

3 EVALUATING AND PLANNING DAS SERVICES

Planning activities aim to determine the design and specify the operating characteristics of the transit lines considered, as well as assign the appropriate resources. Most such activities and resulting decisions must operate according to the policies and within the limits (e.g., on resource utilization) of the corresponding transportation system and help attain the goals (e.g., service levels and target populations) set to it. The study of these policies, limits, and goals may also be part of the planning processes. We denote *evaluation*, the part of the planning process dedicated to the study of the behavior of transit lines, either as stand-alone systems or as part of broader-scope studies at the level of the city. In the following, we identify the main planning and evaluation issues, together with commonalities and differences among DAS, DAR, and traditional transit services.

3.1 Planning Issues

Planning activities are usually described following the well-known distinction among the hierarchically connected *strategic*, *tactical*, and *operation* decision levels. Schematically, for traditional transit services, strategic planning selects the territory and target-population to serve, fixes service levels, selects and assigns the fleet (number and type of vehicles), and designs the system in terms of line routes. Timetables and vehicle routes are part of the tactical planning phase, whereas the operational adjustment of lines is minimal, if any, except when Intelligent Transportation Systems are deployed providing the means to modify the pacing of vehicles and, eventually, bypass some stops. For a more in-depth discussion of planning issues in traditional transit systems, see [1]. Comparatively, purely on-demand services such as DAR, require little strategic design, mainly to define service areas, service levels, and the composition of the fleet. The most important planning process for DAR takes place at the operational level, when routes and schedules are determined little time before actual operations and are possibly dynamically modified once service has begun.

The case of DAS is more complex, because it combines characteristics of traditional and on-demand systems and, thus, requires full planning activities at all three levels. Similarly to traditional services, the strategic level defines the region and target population served by DAS lines, the desired levels of service, the fleet mix, and so on. The line design for DAS is a more complex operation, however, because it requires not only to determine the basic route of the line, but also to select the compulsory and optional stops, thus fixing the maximum deviation from the basic route, as well as determine the time windows associated with the compulsory stops. One thus identifies two sets of decisions in this process: a strategic set, dealing with the basic route and compulsory stop selection, and a tactical one defining the *master* schedule of the line. The latter defines the sequence of compulsory stops, the optional stop segments, and the time windows of the compulsory stops. The master schedule plays the same role for the transit authority and the passive users of the system as the schedule in traditional transit systems. These issues are addressed in [7, 2]. Differently from traditional services, the actual schedule is built during operations, to incorporate into the route of each vehicle the optional stops corresponding to the accepted user requests, while respecting the time windows constraints imposed by the master schedule. The latter has been addressed in [6] (see also [12]).

3.2 Evaluating DAS Services

Part of transportation planning concerns the evaluation of the behavior and performance of a given system under various conditions with respect to demand, regulations and policies, tariffs, and so on and so forth. Such analyzes are usually undertaken in "laboratory" conditions by defining scenarios to represent possible conditions and then simulating the operation of the system. Evaluation activities may be undertaken for a particular line or group of lines as stand-alone systems or as part of planning activities of the transportation system of a city or region. Section 4 details the proposed framework for evaluating a DAS line. In the following, we focus on the differences between DAS, DAR, and traditional transit lines with respect to these issues.

The evaluation of transit lines as stand-alone systems aims to tune operating parameters impacting the system performance, to draw contingency plans, and to derive performance measures under various scenarios for cost-benefit analyzes and integration into system-wide evaluation methods. It generally proceeds according to a sequence where

1. the scenario is specified, defining, in particular, the rules and policies to follow, the territory and potential demand to serve (in more sophisticated methods, the determination of demand constitutes a separate step), the level of service, etc.;

2. the line is designed;

3. the operation of the line is simulated, given the scenario parameters, for a pre-defined time by varying the parameters of interest, e.g., the particular demand, the traffic conditions, etc.;

4. results are collected and performance measures are computed.

Differences between DAS, DAR, and traditional transit may be observed in the complexity of the steps of this process. Thus, Step 3 is rather simple for traditional transit lines, as it consists in generating station-to-station trip demands and loading the vehicle. DAR systems, on the other hand, do not require the design step, while the simulation of operations requires generating trip demands and building the vehicle tour. For DAS, both steps must be performed, each requiring the simulation of several decision as indicated in the previous subsection.

Transit lines are also part of comprehensive models of the transportation system of a city or region. These models integrate demand and mode-choice modeling, as well as a representation of the transportation supply of the region, i.e., the multimodal transportation infrastructure and services. The latter generally includes private (e.g., automobile, bicycles, and pedestrian) and public (e.g., bus lines, light rail, etc.) transportation means, as well as, sometimes, an approximation of the freight-vehicle flows. The assignment of demand to the transportation network supply, according to the behavior of the various classes of users considered, provides the means to simulate the behavior and performance of the transportation system. Several methods and software instruments are available to perform such studies (see, for example, [8, 3]).

So-called static methods simulate the transportation system for an average demand, often during peak-hour periods. Traditional transit lines are represented through their fixed lines and headways, and particular assignment algorithms are used to compute the passenger itineraries using these lines (and private transportation means, eventually). DAR lines are not usually represented, due to the non-regularity of their lines and operations. Similar issues are also partially affecting the representation of DAS lines. Yet, due to its regular service component, a DAS line could be specified by introducing the basic route and compulsory stops, together with average travel times derived from a stand-alone evaluation of the line.

Methods based on Dynamic Traffic Assignment principles are increasingly used to analyze the time-dependent behavior of transportation systems. Traditional transit lines start to be represented in such systems (e.g., Dynameq, at http://www.inro.ca), vehicles being followed according to their planned schedule (headway and average speed). A representation of DAS lines similar to the one described for static models could also be used in this case. Yet, given the dynamic nature of such simulations, a challenging perspective is available for DAS lines. A simulation of the DAS line, similar to Step 3 of the stand-alone procedure described above, could be called upon to generate an actual line and vehicle schedule to be integrated into the dynamic traffic simulator.

In both static and dynamic cases, research is required to study the integration of DAS to existing simulators. Both also require, however, the stand-alone simulation capability of a DAS line. This is the topic of the next section.

4 EVALUATING A DAS LINE

We now present the evaluation framework we propose for evaluating DAS services. The framework details the scheme indicated in the previous section and aims to address the challenges of the complex structure of DAS. It is based on simulation and includes the scenario input, the optimization modules for the design and operation of the line, the simulation module for the latter, and the overall simulation control that will yield the statistical information on the performance of the line with respect to the desired measures. Figure 2 illustrates the proposed evaluation framework.

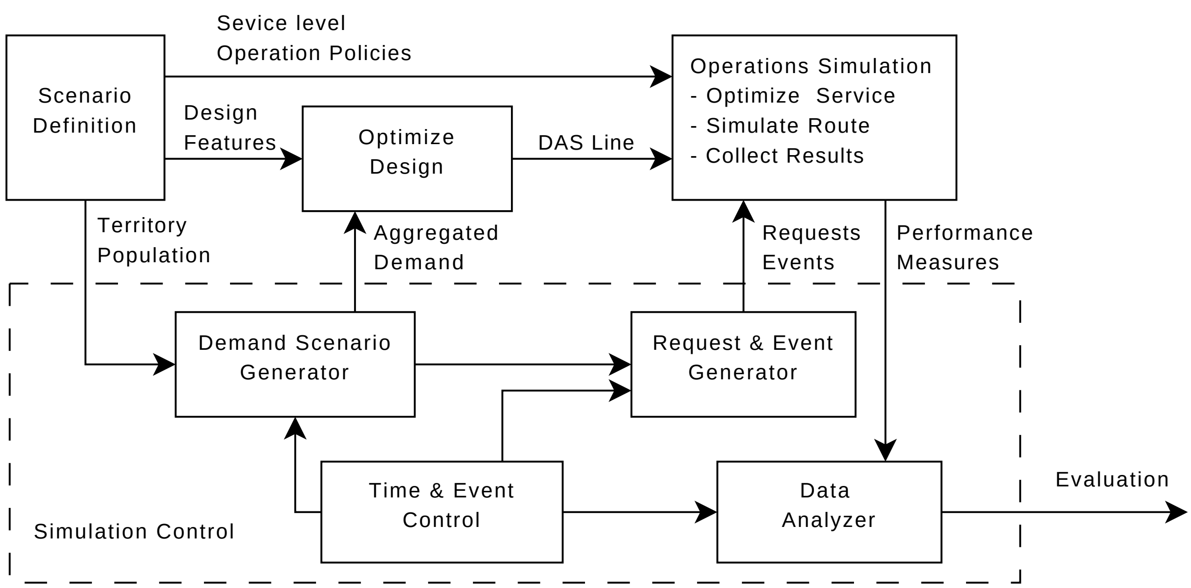


Figure 2: Evaluation Framework for a DAS Line

The figure presents the framework in its most general utilization, where both strategic-tactical and operation planning activities are simulated for a DAS line: Given the data of the selected scenario, aggregated demand figures are generated for the time period defined by the scenario; These are fed to the Optimize-Design unit, which produces a DAS line design given the design features specified by the scenario; The operation of the line is then simulated for a given period of time and randomly generated customer requests and "disturbing" events (e.g., delays, incidents, bad weather conditions, vehicle breakdowns, etc.). The statistical results of this simulation - the Performance Measures of Figure 2 - are then combined to other relevant data to yield the complete evaluation of the system. Simpler utilization modes are possible as indicated in the following.

The scenario information completely defines the case: The territory, its transportation network and characteristics (type of artery, length, average speed, congestion information, etc.), and points of interest, where compulsory stops could be located; The potential population to be served by the system, its spatial distribution and density, its socio-economic information, and any other information conducting to defining the demand; The features and criteria of the contemplated line; The rules and policies of operating the line; and so on. The scenario also includes data required to control the simulation: the modules to activate (e.g., is the line given or it must be designed?), the time length of the simulation, how it is divided into periods, and how the simulation advances through time, the parameters of the random generation of aggregated demand (eventually), customer requests, and disturbing events, etc. It is by varying some of these parameters that one computes expected performance measures under various conditions, builds a comprehensive image of the behavior of the systems, analyzes policies, and determines contingency plans. The parameters most often varied are the ones defining the line design and operation, as discussed in the following.

In its most simple version, the Demand Generator inputs the information relative to the aggregated demand, station-to-station, to the Design module. A sophisticated version would include econometric mode-choice models that, through feed-back loops, would generated this demand taking into account the simulated performance of the line. The aggregated demand is also an input to the request generator, which feeds the line operation simulator.

The line Design Optimizer box corresponds to the strategic-tactical planning level of the system. Except for the simple case when the line is given as a scenario parameter and the process reduces to the simulation of the line operation, a set of optimization models and methods yield a DAS line defined by compulsory stops, segments, and master schedule. The strategic and tactical planning for DAS and the corresponding optimization models and methods require a number of choices be made and the tuning of several parameters. A detailed analysis of these issues is beyond the scope of this paper, but may be found in [7, 2]. We mention a few, however, to illustrate the possibilities provided by DAS services and the richness of the evaluation framework: The line may operate the same design all day or may operate different designs at particular time periods during the day to better fit the expected demand; The relative importance of operation cost and time spend by users on the bus directly influences the final design; Compulsory stops may be selected based on an *attraction* measure; there are several such measures, e.g., total demand out of and into the stop, and corresponding threshold values and, thus, several possibilities for compulsory-stop selection and line designs; The time windows at compulsory stops are computed based on a desired probability of being able to serve all demand points, which threshold value (better than 95% in our current experiments) also impacts the final design and performances; and so on.

Simulating the DAS line requires for each planned departure to generate the actual station-to-station customer requests and the number of people showing off at compulsory stops for trips with destination other compulsory stops. Methodology to select request and to determine the final route and schedule of the vehicle is introduced in [6]. Several operation policies are possible, however, particularly with respect to the treatment of the requests which, for reasons of incompatibility with time windows at compulsory stop, cannot be served as given by the users [13]. Requests may be simply rejected or users could be offered an alternate transport. Requests could also be modified, e.g., postponed to the next vehicle departure or the pick up or alighting stop (or both) may be performed in the vicinity of the requested stop (at the closest compulsory stop, in the worst case). The particular policy, the type of exchanges with the user, the amount of penalty paid when service is not performed as required, etc., all impact the cost and performance of a DAS service. They are thus part of the scenario data and may be evaluated by the proposed framework.

Once the operations of a DAS line have been simulated, a number a solution parameters are observed and statistics computed. According to the kind of analysis one desires to perform, several set of parameters could be interesting in revealing and quantifying different aspects of the system behavior: routing costs, revenue, ride time of the line, total passenger travel time, worst and average ratio between actual and ideal (shortest) travel time for passengers, number of accepted, rejected, delayed or modified requests, user waiting time at compulsory stops, vehicle waiting (dead) time at compulsory stop for early arrivals, etc. Of course, for each scenario, a number of simulation repetitions should be performed to ensure statistical credibility to the analysis results.

5 CONCLUSIONS

Demand-adaptive transit systems display features of both traditional fixed-line bus services and purely on-demand systems: They offer demand-responsive services within the framework of traditional scheduled bus transportation. DAS transit services involve a complex set of planning activities made up of many interrelated decisions. The main steps and goals of the planning activities are the same for traditional and demand-adaptive transit systems. Yet, the particularities of DAS services make for a different planning process and require the development of new methodologies. This differentiation also impacts the evaluation processes of DAS lines, either as stand-alone systems or as part of broader city-wide planning activities.

We described DAS and identified the differences with traditional transit and dial-a-ride systems. We then described the impact of these differences on the evaluation and planning processes of DAS. Finally, we provided a framework for the evaluation of DAS lines that reflects the complexity and flexibility of DAS and accounts for the elements that impact its behavior and performance.

Acknowledgments

While working on this project, Dr. Teodor Gabriel Crainic was NSERC Industrial Research Chair on Logistics Management and Adjunct Professor at the Department of Computer Science and Operations Research, Université de Montréal, Canada, and the Department of Economics and Business Administration, Molde University College, Norway. Partial funding for this research was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) through its Industrial Research Chair and Discovery Grant programs, the partners of the Chair, CN, RONA, Couche-Tard, the ministère des Transports du Québec (MTQ), and the Fonds québécois de recherche sur la nature et les technologies (FQRNT) through its Team Project Grant program. This research was also partially funded by Regione Lombardia, Italy, through its INGENIO grants.

References

[1] Ceder, A. and Wilson, H.M. Public Transport Operations Planning. In *Design and Operation of Civil and Environmental Engineering systems*, pages 395–434. John Wiley & Sons, Inc., New York, 1997.

[2] Crainic, T.G., Errico, F., Malucelli, F, and Nonato, M. Designing the master schedule for demand-adaptive transit systems. In *Proceedengs of the 7th International Conference on the Practice and Theory of Automated Timetabling, PATAT*. To appear, 2008.

[3] Crainic, T.G. and Florian, M. National Planning Models and Instruments. *INFOR*, 2008. forthcoming.

[4] Crainic, T.G., Malucelli, F, and Nonato, M. A Demand Responsive Feeder Bus System. In *CD-ROM of 7th World Congress on Intelligent Transport Systems*. 7WC-ITS, Torino, Italia, 2000.

[5] Crainic, T.G., Malucelli, F, and Nonato, M. Flexible Many-to-few + Few-to-many = An Almost Personalized Transit System. In *Preprints TRISTAN IV - Triennial Symposium on Transportation Analysis*, volume 2, pages 435–440. Faculdade de Ciências da Universidade de Lisboa and Universidade dos Açores, São Miguel, Açores, Portugal, 2001.

[6] Crainic, T.G., Malucelli, F, Nonato, M., and Guertin, F. Meta-Heuristics for a Class of Demand-Responsive Transit Systems. *INFORMS Journal on Computing*, 17(1):10–24, 2005.

[7] Errico, F. *The design of flexible transit systems: models and solution methods*. PhD thesis, Politecnico di Milano, Italy, 2008.

[8] Florian, M. Models and Software for Urban and Regional Transportation Planning: The Contribution of the Center for Research on Transportation. *INFOR*, 46(1):29–50, 2008.

[9] Hickman, M. and Blume, K. A Method for Scheduling Integrated Transit Service. In *Proceedings of the 8th International Conference on Computer-Aided Scheduling of Public Transport (CASPT)*, 2000.

[10] Horn, M.E.T. Multi-modal and demand-responsive passenger transport systems: a modelling framework with embedded control systems. *Transportation Research Part A: Policy and Practice*, 36:167–188, 2002.

[11] Ioachim, I., Desrosiers, J., Dumas, Y., and Solomon, M.M. A Request Clustering for Door to Door Handicapped Transportation. *Transportation Science*, 29(1):63–68, 1995.

[12] Malucelli, F, Nonato, M., Crainic, T.G., and Guertin, F. Adaptive Memory Programming for a Class of Demand-Responsive Transit Systems. In Voß, S. and Daduna, J.R., editors, *Computer-Aided Scheduling of Public Transport*, volume 505 of *Lecture Notes in Economics and Mathematical Systems*, pages 253–273. Springer, Berlin, 2001.

[13] Malucelli, F, Nonato, M., and Pallottino, S. Some Proposals on Flexible Transit. In Ciriani, T.A., Johnson, E.L., and Tadei, R., editors, *Operations Research in Industry*, pages 157–182. McMillian, 1999.

[14] Quadrifoglio, L., Dessouky, M.M., and Palmer, K. An Insertion Heuristic for Scheduling Mobility Allowance Shuttle Transit (MAST) Services. *Journal of Scheduling*, 10(1):25–40, 2007.

[15] Toth, P. and Vigo, D. Fast Local Search Algorithms for the Handicapped Persons Transportation Problem. In Osman, I.H. and Kelly, J.P., editors, *Meta-Heuristics: Theory & Applications*, pages 677–690. Kluwer Academic Publishers, Norwell, MA, 1996.