Public transport operation is inherently connected with uncertainty, starting from schedules created for hypothetical operational conditions and demand levels, operational disturbances, dynamic real demand uncertainty and on complex interactions between different lines and transport modes ending. In this context the realisation of the general public transport objective: maintenance in the long-term horizon the guaranteed mobility standards in the city and their surroundings with essential reduction of transport operational negative impacts, calls for Advanced Public Transportation System (APTS) based dedicated approach. In this paper the exploration of Intelligent and Integrated DISpatching CONtrol (DISCON) method capabilities using new available in APTS capabilities was proposed. The uncertainty and stochastic aspects visible in public transport operation create the demand for dedicated intelligent dispatching robust control proposals. The APTS monitoring and surveillance tools and effective communication media make it possible to realize it in “control by opportunity” mode and with dynamic intelligent control feedback. In this paper DISCON robust dispatching real-time control proposals are presented. The first in LQG robust Kalman filter based control perspective and existence of control and state operational constraints. The second one based on cooperation with multi-criteria PIACON traffic control method as multi-criteria individual traffic - public transport integrated approach with compromise solutions represented by so called “reference trajectory”. In the last case the necessary control actions are recognized by real-time detection of the bus arrival to the signalised intersection and evaluation of its measure off-schedule deviations and bus load. Next the dynamic trade-offs with conflicting intersection users demands and service standards are established by PIACON control method and admissible priority control options in terms of so called “reference trajectory” for DISCON control method are proposed. Illustrative practical examples for all new DISCON options are presented.

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Keywords: APTS systems; public transport; dispatching robust control; LQG control; DISCON; PIACON.

* Corresponding author. Tel.: +012-6341568; fax: +012-6341568.
E-mail address: aad@agh.edu.pl
1. Introduction

The provision of the high quality on-time and reliable service in public transport is a key operational problem which affects both travelers (service standards), transit operators (best use of existing resources) and the city community (potential of public transport to mitigate of the congestion related problems). In practice the efficient solution of this problem is difficult therefore frequently some intuitive ad hoc planning and control actions are proposed. Difficulties result from high complexity of the plant: a large-scale, geographically distributed, multi-goal and functionally non-homogeneous system with the fast dynamics and high complexity of the component processes (occurrence of unpredictable operational events and random disturbances, operation of the driver-vehicle complex, interactions from other vehicles, passengers demand and system environment). This is why on the real public transport lines the off-schedule deviations if not properly compensated by real-time dispatching control actions are amplified by positive feedback mechanisms (e.g. bunching phenomenon), and propagate along the route. This cause an increase in passengers trip and waiting times, transfer/arrival time uncertainty and overload of the buses. In consequence, the lower service performance in natural way influences the choice of mass transit modes. Additionally, the off-schedule working buses negatively influences the service level of the individual transport e.g. by generation of congestion favorable conditions and additional priority calls at the traffic signalized intersections. In the literature for small systems very simplified off-line holding strategies was proposed (e.g. Newell and Potts (1964), Osuna and Newell (1972), Barnett (1974), Newell (1974), Zhao et al. (2006), Daganzo (2009)). The bunching explanation was intuitive and based on simplified assumptions of passengers uniform arrivals and service times at bus stops dominated by boarding processes. The typical deal with this problem was inserting slack time into their schedules, enforcing latter at control points. The idea of inserting slack times and holding buses at fixed control points to depart on time is above 50 years old and in the context of present available technologies and APTS systems solutions seems to have only historical meaning. For analytical models and single/multi criteria optimal solutions of real problems see in (Adamski 1989-1996). The stochastic dispatching control problems (DISCON method) involving many bus lines, buses and control points was presented in (Adamski 1979-1998, 2001-2007). The DISCON method offered several single/multi-criteria control modes: punctuality mode (i.e. schedule determined by individual buses arrival/departure times to/from bus stops along the routes), regularity mode (i.e. schedule determined by headways between buses), synchronizing mode (i.e. synchronizing of transfers between different bus lines or synchronizing the operation of different bus lines at common lines segments), priority mode (i.e. several single/multiple criteria priority options for buses at signalized traffic intersections) (Adamski 1989-2013). The experience from practical implementation of modern ITS systems stimulate the similar system-wide approaches for APTS systems. Therefore, the research problems concerning the essential improvement of public transport service quality has received high attention in the publications (Adamski, 1980-2013). In the papers (Adamski, 2003,2007,2013) new fundamental principles dedicated to the APTS systems have been formulated: “The solution of nowadays transportation problems in urban areas have to be seek first of all by triads: (triad I) integration, intelligence, information-equipped; (triad E) efficient, economical, ecological-oriented; (triad U) user-oriented, unified, up-to-date-tuned approaches to use of existing resources as primary goal”. The practical implementation of these premises was proposed in the form of the HITS (Hierarchical, Integrated, Intelligent Transportation System) multi-networks, multi-layer, multi-criteria original system platforms in (Adamski, 2007-2013). These platforms are embedded in a nowadays available computer, communication, vehicle location and identification technologies supported by intelligent operational tools. The special emphasis was placed on system-wide integration, intelligence and practical implementation operational specifications aspects. The professional transportation systems demands analysis creates essential premises for the fundamental HITS system development principles. In consequence the adequate multi-layer, multi-level functional system structures can be recognized and expressed in terms of several proposed HITS options dedicated to individual traffic, public transport, city logistics modes. The functionalities of hierarchical HITS management and coordination, adaptation, scheduling, monitoring and surveillance and direct control layers was presented and illustrated by representative practical examples in (Adamski, 2007-2013). The main integration and intelligence premises for this HITS platforms dedicated to ITS and APTS systems are as follows:

Intelligence premises: Systems features: high uncertainty, behavioural anisotropy, traffic complex interactions, fast non-linear dynamics, wide range of stochastic and unpredictable phenomena. The challenging operational system requirements: real-time intelligent supervision, management and control system activities with integration of different technologies. Traffic control and management problems challenges: ill-structured, real-time data and knowledge dependent, traffic situational dedicated robust multi-criteria networks problems. Large hardware and software real-time systems. Fast progress in advanced intelligent technologies, tools and methods. The ITS and APTS systems are in natural way embedded in an interconnected complex of physical/virtual networks called SupNet (Adamski, 2005) see Fig. 1. The SupNet through wide spectrum of complex interactions create the key dynamic and behavioral operational environment for transportation processes (Adamski, 1983-2003). The real-time identification, estimation and prediction of these interactions for APTS system operation purposes are crucial problems conditioning the efficiency and productivity of these systems. In this context the necessary condition for management and control of such systems require both deep understanding of these features and behavior of these systems i.e. understanding operational environment (SupNet) that essentially influences the operation of these systems. This is necessary to rationally optimize the operation of APTS systems both in terms of primary goals (e.g. efficiency, reliability) and in terms of secondary goals of system operational general influences (e.g. minimization of negative environmental impacts). The APTS problems resulting from application of triads of I, E and U with rational use of existing resources as primary system goal are presented in Table 1. The adequate HITS platform with multi-layer functional structure integrating management, surveillance and control actions decision-making and control functions (adaptive control, scheduling, management) was proposed in (Adamski, 2003). The properly integrated such hierarchical structures of ITS-APTS systems (see Fig. 2) creates the basis for unique priority control capabilities and completely new features: multi-criteria system-wide solutions stimulating synergic effects, intelligent real-time opportunity based efficient priority strategies selection, real-time fully adaptive "control by opportunity" and control modes, high control efficiency with operational flexibility and transparency. The practically important flexibility concerns wide spectrum of possible APTS systems priority strategies: PS={passive (p), semi-active (sa), active (a), adaptive (ad)} offering both off-line and on-line tools for realization of various signals plans modifications, starting from off-line transit supporting fixed-time (f-t) signal plans modifications (Adamski, 1980,1989,2006), through on-line real-time transit vehicle actuated (v-a) signal plans modifications (e.g. phase extensions/shortening/skipping (Adamski,
1983-1989, 1994), and on fully real-time adaptive multi-criteria priority control actions ending (Adamski,1989, 1996-2006). Practical aspects are related to adaptability to existing system resources and institutional/ organizational structures. The Fig.2 presents the basic characteristics of the “PRIORITY” strategy offered by the integrated ITS-APTS systems with high flexibility at different layers of the APTS system to simultaneous and heterogeneous priority requests, congestion levels, and inter-lines/ modes transfers. This enables to realize wide spectrum of priority control tasks starting from fully distributed local priority control actions at single intersections, through zones/network modules integrated priority control of groups of vehicles and on network integrated multi-transit lines/modes adaptive dispatching control ending. The ITS system components offers several possible solutions of priority control tasks e.g. intelligent cooperation of intersections controllers with APTS system dispatching control layer (Adamski, 2005). The existence of such operational redundancy is a crucial in APTS systems fault-tolerant operation. The new challenging problem related to information and operational redundancy is concerned to the ambient intelligence priority control solutions providing real-time traffic situations recognized and diagnosed based intelligent/smart services. In this paper the solution of this problem will be a result of operation of an Intelligent Supervisor (IS) in the priority dispatching control loop (see Fig.3). The dedicated control approach has been developed on the basis of pre-assumption that new adaptive and integrated dispatching robust control methods are sufficiently motivated by the existing hardware capabilities (video detectors, GPS systems, on-board computers) integrated with supervisory AIDM and ATIS systems (Adamski, 2000-2005). The embedded into APTS activity of the direct dispatching control layer is concerned with the total integration of the control plant by control structure. The solution of this problem is split into the

<table>
<thead>
<tr>
<th>TRIADS</th>
<th>FUNDAMENTAL PRINCIPLE</th>
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<tbody>
<tr>
<td>Integration</td>
<td>• Integration of individual urban traffic and APTS transit systems operation</td>
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<td></td>
<td>• Integration of APTS by synchronized outer/inner transport modes transfers</td>
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<td></td>
<td>• Integration of demand-related public transport service planning, synchronized multi-lines schedules with real-time dispatching control, surveillance and management actions</td>
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<td>• Integration of ITS data and computer networks infrastructure for APTS applications</td>
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<tr>
<td>Intelligence</td>
<td>• Multi-criteria public transport priority control at traffic intersections and on the arterials with real-time operational preferences generated in real-time by an expert DSS</td>
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<td></td>
<td>• Intelligent supervision (safety, security, operation, maintenance) and intelligent dispatching control</td>
</tr>
<tr>
<td></td>
<td>• Intelligent driver and fleet monitoring, information service and management</td>
</tr>
<tr>
<td></td>
<td>• Efficient utilization of available resources (DSS expert systems)</td>
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<td></td>
<td>• Intelligent fare policy tools</td>
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<tr>
<td>Information</td>
<td>• AVL/GPS/AVI equipment providing real-time information about vehicle location, load, off-schedule deviations</td>
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<tr>
<td></td>
<td>• Passengers Information Service in vehicles and at the bus stops</td>
</tr>
<tr>
<td></td>
<td>• Interoperable data and knowledge bases developed for traffic information service</td>
</tr>
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<td></td>
<td>• Information Agency and Internet website</td>
</tr>
<tr>
<td>Efficiency</td>
<td>• Significant enhance of efficiency of traffic control, supervision, co-ordination and synchronizing actions by computer-based real-time optimization and expert tools.</td>
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<td>• High operational user friendly flexibility realized in real-time dedicated actions mode</td>
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<td></td>
<td>• Integration of transport telematics applications (on-board computers, AVL system)</td>
</tr>
<tr>
<td>Economy</td>
<td>• Economies of scale transit services oriented actions with respect to market size</td>
</tr>
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<td></td>
<td>• Essential increase of the service productivity by the use of integrated vehicle routing and scheduling strategies tailored to the demand pattern. The benefits are the reduced number of vehicles and lower capital and operating costs</td>
</tr>
<tr>
<td>Ecology</td>
<td>• Pro-ecological monitoring and supervision of the technical state of vehicles (diagnosis and maintenance of the vehicle fleet, emissions monitoring, drivers and vehicles supervision).</td>
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<td>• Environmentally friendly cars (e.g. alternative fuels)</td>
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<td>• Pro-ecological oriented attractive public transport alternatives w.r.t. individual cars traffic</td>
</tr>
<tr>
<td>User-oriented</td>
<td>• Advanced Traveler Information Systems Technologies (information transparency and quality) PreTrip; In-Terminal; In-Vehicle, PDA, City Terminals, Depots, Stations, ETC</td>
</tr>
<tr>
<td></td>
<td>• Flexible APTS (easy access, high service standards, security)</td>
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<tr>
<td>Unified</td>
<td>• Compatible with ITS technologies and obligatory standards</td>
</tr>
<tr>
<td>Up-to-date</td>
<td>• AVMS, AVL, GPS, AVI, APC, ATP, ADTB, AGS, ACC, ADAS, OBU, ETC, CAS</td>
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direct dispatching control layer realizing regulatory (schedule follow-up) control providing a stable steady-state operation of the lines, and optimisation layer realizing optimising (transit schedule set-point) control of the steady-state operated processes. In (Adamski, 2003-2006) flexible 1-D and 2-D dynamic network control DISCON method is presented that offering wide spectrum of control capabilities, starting from control of interacting network elements with different levels of aggregation, in space (individual stops, route zones, overall routes), in vehicles population (one vehicle, groups of vehicles) or in time periods (rush hours, transient service periods during a day) and on multi-criteria and robustness features of the dispatching control actions ending.

Fig. 2. Priority connected individual ITS and public transport APTS systems integration
2. DISCON: Public Transport Dispatching Control in APTS System

The 2-D field of buses trajectories (planned and realized) is presented in Fig (4) and create the basis for DISCON dispatching control method 1-D/2-D deterministic and stochastic bus lines state-space equations representations (Adamski, 1989,1993-1998,2003-2007). In general, 2-D state-space vehicle trajectories based model (Adamski, 2002,2007) consist of state vector $x(i,j)$ with coordinates $i$-vehicle and $j$-of possible service-oriented points along the route (e.g. bus stops, terminals, traffic intersections) indices. The input $u(i,j)$ and output $y(i,j)$ vectors are connected with states through bus line control structure-related real matrices of appropriate dimensions and create state-space equations in the form (1). The state-vector is the measure of deviations between planned and actual vehicle trajectories ($x=\text{traj-traj}^s$) In 1-D system representations the planned and actual vehicle trajectories are the functions of 1-D domain. Denoting off-schedule deviations of bus departure times from control points on a route by $x_{ij}=t_{ij}-t_{ij}^s$ and trip times by $z_{ij}=T_{ij}-T_{ij}^s+C_{ij}-C_{ij}^s$ the 1-D punctuality control model can be written in the vector form (Adamski, 1989-1998) where $x_j,u_j$ and $z_j$ are state, control and disturbance (travel times) vectors:

$$ x_{j+1} = A^1_j x_j + A^n_j x_{j-n} + B_j u_j + A^1_j z_j \quad x \in [x_{Lj}, x_{Uj}]; u \in [L_j, U_j]; A^1_j \in \mathbb{R}^{m \times m}; B_j \in \mathbb{R}^{m \times r}; A^n_j \in \mathbb{R}^{m \times m} \quad (2) $$

Using arrival instead of departure times in the above model correspond to simple linear transformation of this punctuality model and it was proposed in (Adamski, 1989). The dual control model i.e. propagation off-schedule deviations $x_i$ of a given vehicle “i” was proposed in (Adamski, 1989). The DISCON dispatching control method minimize of some operational measures of service standards (e.g. off-schedule, off-regular headway, off-transfer windows deviations). Wide spectrum of DISCON dispatching control tasks (punctuality, regularity, synchronizing, priority control) realized in the bottom APTS system direct control layer have been presented in (Adamski, 1989-2011). In these papers the 1-D and 2-D (primal and dual) dynamic control plant representations have been developed and illustrated by a family of single criteria DISCON control solutions of dead-beat, LQ, LQG type. The optimal dispatching control problem may be formulated as (3): where $Q_k, R_k>0$ and $S_k>0$ are weighting matrices.

$$ J_{T-j} = \sum_{k=j}^{T-1} [u_k]^2_{Q_k} + \sum_{k=j}^{T-1} [x_k]^2_{Q_k} + \sum_{k=j}^{T-1} [u_k]^2_{S_k} + \sum_{k=j}^{T-1} [u_k-u_{k-1}]^2_{S_k} \quad (2) $$

$$ \text{PO}_{\text{min}} \ u \quad J_{T-j} = \sum_{k=j}^{T-1} [u_k]^2_{Q_k} + \sum_{k=j}^{T-1} [x_k]^2_{Q_k} + \sum_{k=j}^{T-1} [u_k]^2_{S_k} + \sum_{k=j}^{T-1} [u_k-u_{k-1}]^2_{S_k} \quad (3) $$
The first and second terms represents the off-reference deviations penalties at point (T) and all precedent vehicle stops. The last two terms penalize both the weighted sum of squares of control actions and the weighted sum of squares of the first backward differences in control actions (i.e. the costs of the magnitude of control actions and adaptive control smoother features). The state and controls may be bounded by constraints: $x_k \in [L_k, U_k]$, $u_k \in [U, V]$ or imposed by PIACON methods local reference trajectory constraint $x_k = \text{reftraj}_k$. In this paper the aggregated (zonal) models (ACM) are used for DISCON LQG control solutions with known physical constraints on inter-zonal state variables and disturbances. ACM: Aggregated models in space and population of vehicles are $A = [M_{sl}]$: with intra/inter zone matrices and $s,l=1,..,q$ where $q$ is the number of zones $i=N_{s-1}+1,..,N_s$; $k=N_{l-1}+1,..,N_l$.

$$M_{ll}: \quad a_i = \lambda (1-\lambda)^{N-l-i} \quad i<k; \quad M_{sl}: \quad a_i = \lambda (1-\lambda)^{N-l} \prod_{j=l+1}^{i} (1-\lambda_j) (1-\lambda_i)^{N-i} \quad (4)$$

One of drawback of classical Kalman filtering in this case is not exploration of the above control and state constraints in estimation process which can lead to sub optimal estimates or instability of the error dynamics. To overcome these issues the Kalman cyclically biased estimating process approach has been proposed enabling to solving at each zone an optimization problem with admissible off-schedule deviations state constraints. To illustrate bus line multi-zone LQG stochastic dispatching control problem the following example is presented.

**Data:** Bus line with ten bus stops aggregated in three zones (1-3, 4-7, 8-10 bus stops) and operated ten buses. To illustrate dispatching control capabilities the real observed bunching coefficients were increased ten times (i.e. $K_j = 0.15$ for $j=1,2,3$; $K_j = 0.25$ for $j=4,5,6,7$; $K_j = 0.1$ for $j=8,9,10$). The initial deviations from schedule (i.e. the initial system state is $x_0=[3.2,-1,0.1,-2.1,1.2,2]$). The control lower/upper constraints are $U_j=-L_j=[2,1,2,1,1,2]$. The inter-zonal service synchronization requirements are represented by “synchro window” $x_0 \in [-2.1]$ and off-schedule deviations constraints $|x_k| \leq X$. The uncontrolled and controlled cases with admissible control and state magnitudes are presented in Fig. 5 where $X=3$ and Fig.6 with $X=5$. Reference trajectory priority control offered by DISCON-PIACON control methods interactions is realized in the following way. At first the detection of the bus arrival time to the signalised traffic intersection and evaluation of its measure off-schedule deviation and bus load is realized. After that the dynamic trade-offs between individual and public transport with respect of bus arrival time to the signalised traffic intersection and evaluation of its measure off-schedule deviation constraints are imposed by PIACON methods local reference trajectory constraint $x_k = \text{reftraj}_k$. In this paper the proposed for system-wide exploration and identification in real-time impacts of various traffic-transit-signal timing factors influencing the potential benefits of priority control actions. The IS activity is concerned with hierarchical monitoring and recognition of: stability/controllability features of bus line, artery, intersection dynamics, existence synergic effects symptoms (public/individual transport), impacts of priority control actions at local (split, phases/groups,demands) artery (cycle time, offset, NWP-Nominal Working Points), network (markers, NWP, areas synchronization) levels. The main objectives at local level is to isolate the impacts of various factors (traffic, transit, signal timings) on the potential benefits of priorities and selection of real-time trade-offs by IS. The results of two examples of intelligent priority control impacts are presented in Table 2. The first example illustrate increase the robust control features by IS actions of the PIACON generated “local reference trajectory” for priority control on artery. The robust margins increases by 6-11% by intelligent suggestions of IS (Figs. 1-6, Table 2). The second example illustrates the impacts of a simple priority control actions realized on a single signalised intersection within a coordinated artery. The signal plans parameters are as follows: cycle time $C=40/60/80$(sec); splits $S=20+4*10/80-1*10$; $l=1..5$; $g_{min}=r_{min}=10$(sec); $\Delta g=5-10$(sec); $r_{max}=C-g_{min}$. The traffic demand level $q=800-1600$ (veh/h); $s=1600$ (veh/h) and demand distribution between...
intersection approaches fluctuated in wide limits. The traffic priority control impacts are analysed in the context of the PIACON control method Delay Mode realized usually in this demand range (see Pareto Set for different cycle times Fig7, Table 2). The Intelligent Supervisor IS suggest intelligent modifications of priority control actions in order to marginalize individual traffic disbenefits. The recognition by IS in a given traffic situation of symptoms of synergic effects of priority actions can offered also benefits to individual traffic (Figs: 8,9 and CS=3) or marginalize traffic disbenefits by proper splits modifications (Figs: 10-12 and CS=3-7).

4. Conclusions

The highly effective dynamic on-line real-time control tools for dispatching control in the public transport may be developed by proper integration of the new control mechanisms (hierarchical distributed structure, multi-criteria approach, robust adaptive control actions) with the potential of APTS systems. The main advantages of the presented control approach results from its universal applicability to control tasks met in real public transport network with high dispatching control standards i.e. high flexibility and robust control features guaranty. The adaptive decomposition of bus routes on zones and theirs synchronization is a very attractive from the point of view of the real-time bus networks control problems. Priority dispatching control offered by cooperation of the PIACON-DISCON methods provides benefits to buses depending on actual control situation and requiring

![DISCON: Buses trajectories 2-D field representation](image-url)
priority phase with guaranty of minimal negative impacts on other system users. The priority control impacts in natural way are related to real-time compatibility with actual traffic situations related optimal signal settings i.e. priority actions can enhancing/ deteriorating signal timings and in consequence can generate both benefits and disbenefits. In this context the proposal of implementation of Intelligent Supervisor (IS) equipped with intelligent traffic situations diagnosis tools is of paramount importance. The main advantages of the presented control approach results from its: universal applicability to a wide spectrum of priority control tasks met in the real public transport network (punctuality, regularity, synchronizing) realized on various intersections and arterials; very flexible computer-oriented intelligent priority control network tool capabilities minimizing network-wide priority negative impacts; offered high priority control standards. The main specifications of these control standards includes: ITS system-wide priority efficiency, “control by opportunity” mode, robust control features guaranty; intelligent supervisor actions fully integrated with the priority control loop.

References


Table 2. PIACON-DISCON-Intelligent Supervisor public transport priority control
gmin=rmin=10 (sec); Δg=5-10 (sec); traffic volumes q= 800-1600 (veh/h); saturation volumes s=1600 (veh/h); CS∈[1-7] control situations