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DISCON: vehicle probe reference trajectory based real-time multi-criteria bus priority control at traffic intersections

INTRODUCTION

The existing Vehicle Probe solutions and multiple type high spatial resolution satellite and air based imagery equipped for example with digital orthophotography and integrated with GIS platforms may be a vital source of information about vehicle trajectories random field (VTRF). The available 1m spatial resolution data, supplemented by multi-spectral land cover dataset used for land use interpretation make it possible precisely assign the detected and tracking vehicle trajectories to appropriate lanes.

The wide spectrum of available conventional means of traffic information collection (e.g. GPS-generated locations, video-detectors, lasers, LIDAR, radar) creates supplementary data sources for estimation of VTRF. The first original implementation of VTRF traffic representation for multi-criteria real-time adaptive individual traffic control purposes was developed in PIACON (Polyoptimal Integrated Intelligent traffic Adaptive CONtrol) method ([6][9][12][16-18] and[19-22]). In these control problems VTRF representation of traffic enables to use completely new travel smooth measures as performance criteria. It create from one site the possibility of direct representation in control problems until now not available LoS (Level of Service) standards represented in natural way by individual trajectories and their characteristics (e.g. various trajectories related smoothness measures representing for example stops, delays, queues, unsafe interactions, driver discomfort) in terms of whole O-D related individual trips. In addition by family of VTRF trajectories the service standards offered by various parts of transportation system (e.g. links, intersections, arteries, sub-areas) may be integrated. The knowledge included in VTRF gives unique opportunity for real-time intelligent adaptive traffic robust control actions dedicated to real-time on-line recognized operational functionality of various parts of the network e.g. completely novelty PIACON artery multi-criteria traffic progression synchronizing [20] and bus priority control with VTRF related on-line real-time estimated control performance measures [18].The adequate HITS platform functional structure with multi-layer management, surveillance and control actions integrating broad spectrum of decision-making and control functions (adaptive control, scheduling, management) was proposed in ([13-15] and [23-25]). The ITS systems create co-operative platform for APTS systems. The properly integrated hierarchical management, surveillance and control structures of ITS and APTS systems (see Fig. 1) creates the basis for unique priority control capabilities and completely new features: integrated 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 robust control modes, high control efficiency and productivity 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 ([26-28] and [31-32]) on-line tools for realization of various signal plans proposals, starting from off-line transit supporting fixed-time (f-t) signal plans modifications ([1-5][7-11][22]), through on-line real-time transit vehicle actuated (v-a) signal plans modifications (e.g. phase extensions /shortening /skipping ([2][3][5]), and on fully real-time adaptive multi-criteria priority control actions ending ([3][8-12]. The Fig.1 presents the basic characteristics of the “PRIORITY”
strategy offered by the integrated ITS-APTS systems with high flexibility to simultaneous and heterogeneous priority requests, congestion levels, and inter-lines/modes transfers. The priority request due to flexibility can be initiated at different layers of the APTS system. 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 direct dispatching control layer ([14],[16]). The existence of these 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 ([29-30]) based intelligent/smart services. In this paper the solution of this problem will be a result of PIACON intelligent multi-criteria “bus reference trajectory” selection to be a “virtual schedule” for the DISCON priority dispatching control activity. 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 ([3],[11-14]). 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 direct dispatching control layer realizing regulatory (schedule follow-up) control providing a stable steady-state operation of the lines, and optimization layer realizing optimizing (transit schedule set-point) control of the steady-state operated processes.

Fig. 1. Priority connected individual ITS and public transport APTS systems integration
1 BASIC DISCON PUNCTUALITY CONTROL MODEL

The 2-D bus trajectories random field (BTRF) model representations of the planned and realized services are presented in Fig (2). It creates the basis for the DISCON control method 1-D/2-D deterministic/stochastic bus lines state-space equations representations ([3-4][7-8] [10-16][23]). In general, 2-D state-space vehicle trajectories based model ([13][23]) consist of state vector \(x(i,j)\) with 2-D coordinates \(i=1\) bus index \(,i^1\) and \(j=J\) index of possible points along the route (e.g. bus stops, terminals, traffic intersections). 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 the state-space equations in the form (1). The state-vector represents the deviation between planned and actual vehicle trajectories \(x(j=\text{traj}_j)\)

\[
x(i + 1, j + 1) = \sum_{l=0}^{2} \left\{ A_{j} x(i + l(l - 1) / 2, j + l(2 - l)) + B_{j} u(i + l(l - 1) / 2, j + l(2 - l)) \right\}; \quad y(i, j) = C \cdot x(i, j) \tag{1}
\]

In 1-D system representations the planned and actual bus trajectories are the functions of 1-D domain. Denoting off-schedule deviations of bus departure times from control points on a route by \(x_{ij}=t_{ij}-t_{j}^s\) and trip times by \(z_{ij}=T_{ij}-t_{j}^s+C_{ij}-t_{j}^s\) the 1-D punctuality control model can be written in the vector form ([3-8][10]) where \(x_{ij}, u_{ij}\) and \(z_{ij}\) are state, control and disturbance (travel times) vectors.

\[
x_{j+1} = A_{j} x_{j} + A_{j}^n z_{j} + B_{j} u_{j} + A_{j}^l z_{j} \quad x_{j} \in [x_{Lj}, x_{Uj}] \quad u_{j} \in [L_{j}, U_{j}] \tag{2}
\]

\[
A_{j}^1 \in R_{mxm}^{max}; B_{j} \in R_{mxr}^{max}
\]

are lower triangular diagonally dominated matrices with non-zero elements: \(a_{ik}=\lambda_{i}\Pi_{l=k+1...}(1-\lambda_{i}); b_{ik}=a_{ik}/\lambda_{k}\) where \(\lambda_{k}\) are eigenvalues of \(A_{j}^1; A_{j}^n \in R_{mxn}^{max}\) is a matrix with the last non-zero column equal to \(c_{im}=(-1)^{i+n+1}\Pi_{l=1...}(1-\lambda_{i})\).

Using arrival instead of departure times in the above model corresponds to simple linear transformation of punctuality model and it was proposed in [3]. The dual control model i.e. propagation off-schedule deviations \(x_{i}\) of a given vehicle “i” was also proposed in [3].

The DISCON dispatching control method minimize of some selected operational measures of service standards (e.g. off-schedule, off-regular headway, off-transfer windows deviations). Wide spectrum of DISCON control tasks (punctuality, regularity, synchronizing, priority control) realized in the bottom APTS system direct control layer have been presented in [3-24]. 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 minimize the criterion as (3), where \(Q_{k}, R_{k}>0\) and \(S_{k}>0\) are weighting matrices.

\[
J_{F-j} = \|x_{F}\|_{Q_{j}}^2 + \sum_{t=0}^{l-1} \|x_{t}\|_{Q_{j}}^2 + \|\mu_{t}\|_{Q_{j}}^2 + \|\mu_{t} - u_{t-1}\|_{S_{j}}^2 \tag{3}
\]

In this paper the DISCON priority control of the bus at traffic signalized intersections is realized under the following DISCON punctuality control model modifications. The “reference trajectory” \(\text{reftraj}_j\) imposed by PIACON method for bus i-th at j-th intersection is treated as “virtual schedule” (i.e. \(x_{i}(j)\) is off-schedule deviation). Reference trajectory priority control offered by DISCON-PIACON control methods interactions is realized in the following way by dynamic intelligent traffic control feedback (see Fig. 3). At first the detection of the bus arrival time to the signalized 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 conflicting traffic and robust criteria (expressed in terms of norms of the Hardy spaces \(H_{2}\) and \(H_{\infty}\)) demands are established by PIACON method and appropriate robust local reference priority options called the “local bus reference trajectory” for DISCON dispatching control activity are proposed. For DISCON control actions the system (2) is represented by \(x_{j+1} = A_{xj} + B_{uj}\) deterministic state equation and discrete LQR optimal priority control problem (4) with this state equation is analytically solved.
The following assumptions are obligatory: the pairs of $(A, B)$ is controllable (i.e. d-stabilizable) and the pair of $(Q^{1/2}, A)$ is detectable. The original DARE Riccati equation $X = A^T X A + Q - A^T X B (R + B^T X B)^{-1} B^T X A$ was transformed to equivalent form $X = A^T X (I + B R^{-1} B^T) X A^{-1} A + Q$ and analytical solution $X = M_2 M_1^{-1}$ is determined with generalized eigenvalue and eigen-vector problem: $F_1 M^* \text{diag}(\lambda) = F_2 M$ where $M = [M_{11}, M_{12}; M_{21}, M_{22}]$ is a matrix of generalized eigenvectors, $F_1 = [I \ B^T \ 0 \ 0^T]$ and $F_2 = [A \ 0 \ -Q \ I]$. To illustrate this solution the simple example was presented.

Example: To illustrate priority control capabilities the real observed bunching coefficients were increased ten times i.e. $K_1 = 0.25$ and the analytical control solution $u = -(R + B' X B)^{-1} B' X A$ is as follows: $M_{11} = [0.4491 \ 0.3333; 0.2169 \ 0.2540]; M_{21} = [1.0000 \ 0.2593; 0 \ 1.0000]$ $X = [4.7366 \ -5.1960; -5.1960 \ 10.7572]$ and optimal control $u = [-1.5035 \ 1.2077]$.

In Table 1 the practical examples from public transport “bus reference trajectories” priority control actions on the Cracow artery (Al. Trzech Wieszczy) are presented. Very high benefits of this proposed control approach results among others from analytical control solutions at the DISCON activities and high robust control features of these control actions.

In this paper the adequate diagnosis of the preference structures by Intelligent Supervisor (IS) working in APTS intelligent supervision layer is proposed for PIACON multi-criteria control method that in real-time selects of these reference trajectories. This enables 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/controlability features of bus line, artery, intersection dynamics, existence of the 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 different examples of intelligent reference-trajectory based multi-criteria priority control solutions are presented in Table 1.

The examples illustrates lack of bus priority control related impacts on the individual traffic and increase the robust control features of the PIACON generated “local and several intersections related reference trajectory” for priority control actions on the artery. These examples illustrates also high flexibility the traffic situations related simple priority control actions realized on a single signalized intersection within a coordinated artery. The signal plans parameters are as follows: cycle time $C = 40/60/80$(sec); splits $S = (20+1*10)/(80-1*10)$; $l_1 = 1.5$; $g_{min} = r_{min} = 10$(sec); $\Delta g = 5 -10$(sec); $r_{max} = C - g_{min}$. The traffic demand level $\{l = 800 - 1600 \ (veh/h) ; s = 1600 \ (veh/h) \}$ and demand distribution between intersection approaches fluctuated in wide limits. The traffic priority control impacts are analyzed in the context of the PIACON control method Delay Mode realized usually in this demand range (see Pareto Set in Fig 4-5, Table 1). The Intelligent Supervisor IS may suggest intelligent modifications of preference structures (see Fig. 5 in Table 1) and in consequence different 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 or marginalize traffic disbenefits by proper splits modifications.

CONCLUSIONS

New highly effective dynamic on-line real-time control tools for dispatching priority control in the modern APTS hierarchical systems may be developed first of all by proper integration of the new technologies and system-wide decision making mechanisms (hierarchical integrated structure, multi-criteria approach, robust adaptive control and management actions) with the potential of intelligent tools implemented in dedicated way in APTS systems. The main advantages of the presented control approach results from its analytical related universal applicability to priority control tasks met in the real public transport network with high offered service standards i.e. high flexibility and robust
control features guaranty. The adaptive decomposition of bus routes on zones and theirs inter-modal compatible synchronization is a very attractive from the point of view of the real-time bus networks control problems. Priority real-time dispatching control actions offered by cooperation of the PIACON-DISCON methods provides benefits to buses in intelligent way depending on the actual control situation and requiring by bus priority signal phase with guaranty of minimal negative impacts on the 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 multi-criteria PIACON control method supported by 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 analytical solutions: 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.

![Fig. 2. DISCON: Buses trajectories 2-D field representation](image)
**Abstract**

The challenging dispatching control problems in public transport involve high level of demand and operational dynamic uncertainties and complex interactions between different lines and transport modes. The communication technologies supported the ITS-APTS systems enables the exploration of the Vehicle Probe and...
GPS based real-time data for dispatching control actions compensating off-schedule deviations. In this paper the “control by opportunity” ITS systems principle is used with adequate DISpatching COntrol (DISCON) method “priority control option” mode extensions dedicated to the new real-time multi-criteria intelligent bus priority control at the traffic intersections. This proposal involves bus reference trajectory related control actions and interactive cooperation of DISCON with PIACON real-time multi-criteria individual traffic control method. This enables the 2-D multi-criteria bus priority control actions dedicated to artery and bus trajectory functionalities (e.g. passenger transfers standards). In this context the dynamic trade-offs between conflicting intersections users demands and system service standards can be established by PIACON control method in terms of compromise solutions. In consequence an multi-criteria dispatching priority control option called “reference trajectory” for DISCON dispatching control method can be proposed. Illustrative practical examples for these multi-criteria intelligent DISCON priority control options are presented.

DISCON: Wielokryterialne priorytetowe sterowanie autobusami na sygnalizowanych skrzyżowaniach ruchu bazujące na referencyjnych trajektoriach

Streszczenie
Problemy stanowiące wyzwania dla sterowania dyspozycyjnego komunikacji zbiorowej to dynamiczna nieokreśloność popytu i warunków operacyjnych oraz złożone interakcje między różnymi liniami i modami transportowymi. Dostępne technologie ICT wspierane ITS-APTS systemami umożliwiają wykorzystanie dostępności danych w czasie rzeczywistym z VehProbe i GPS dla inteligentnego sterowania dyspozycyjnego w czasie rzeczywistym. W artykule tego typu zasada “control by opportunity” z ITS systemów jest realizowana przez priorytetową opcję dyspozycyjnego sterowania metody DISCON dla której tzw. 2-D trajektoria referencyjna jest wyznaczana przez wielokryterialną metodę sterowania ruchem indywidualnym w czasie rzeczywistym PIACON. Istotną zaletą proponowanego podejścia oprócz inteligencji jest uwzględnianie przy priorytetowym sterowaniu wielu uczestników ruchu na skrzyżowaniach oraz integracja celów sterowania ruchem indywidualnym (np. synchronizacja) i komunikacją zbiorową (funkcjonalności trajektorii pojazdów). Lokalny zasięg referencyjnej trajektorii umożliwia analityczne rozwiązanie problemu priorytetowego sterowania przez metodę DISCON.

REFERENCES