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ITS: Intelligent Transportation Systems – Multi-Criteria Control Problems

1. ITS system platform multi-layer interactive structure

The proposal of multi-layer ITS system functional, physical and information structure was presented in (Adamski 2002, 2003). In this system the behavioural interactions (interfaces) between layers in a crucial way determines the features of the whole system operation (Adamski 1993, 1995, 1998, 2002, Adamski, Florek 1997, 1999) In this context we can differentiate three main interactive cycles (interfaces) between system layers (see Fig. 1) that must to guaranty first of all the stable (fixed point Banach theorem) operation of the whole system and in this perspective to offeren effective operation of individual layers. The dynamical behavioural interactions are in general very complex because they are motivated by many uncertain and not directly measurable premises; e.g. user habits and inertia, driver memory, learning processes, access to information, interactions from ATIS (Advanced Transportation Information System), VMS (Adamski 1992). The existing publications concerning the simple one cycle static interactions (route choice – simple signal control) indicates the possibility to converge system trajectory to different types of attractors (fixed-point, k-periodic, quasi-periodic or chaotic) (Cantarella 1993, Cea *et al.* 2008, Meneguzzo 1997). Therefore, the ARIMA(n_i, m_i) models was selected to adequately represents the behavioural patterns dedicated to different layers with entropy-related estimation and calibration of the parameters (Adamski 1998, 1999, Adamski, Florek 1997, 1999). These layers are working in dedicated time reaction horizons ($T_i = n_i T_{i-1}$) therefore inter-layer macro ARIMA models can be used with system integration premises. The main paradigm presented in this paper may be formulated as follows: to propose truly multi-criteria entropy compatible ITS multi-layer dynamically interactive system functional structure. The entropy compatibility is guaranteed by the MLE demand estimators of trip generators/attractors, relative entropy-based behavioural mechanisms (Adamski 2002, 2003), entropy/modal entropy maximization criteria and multi-criteria control actions (i.e. robust H^∞ – stochastic efficiency (LQG) trade-offs) (Adamski 2003, 2005). The next very important feature of the proposal is truly multi-criteria (i.e. compromise set based) and simultaneous ITS application-oriented optimisation of the whole network processes.

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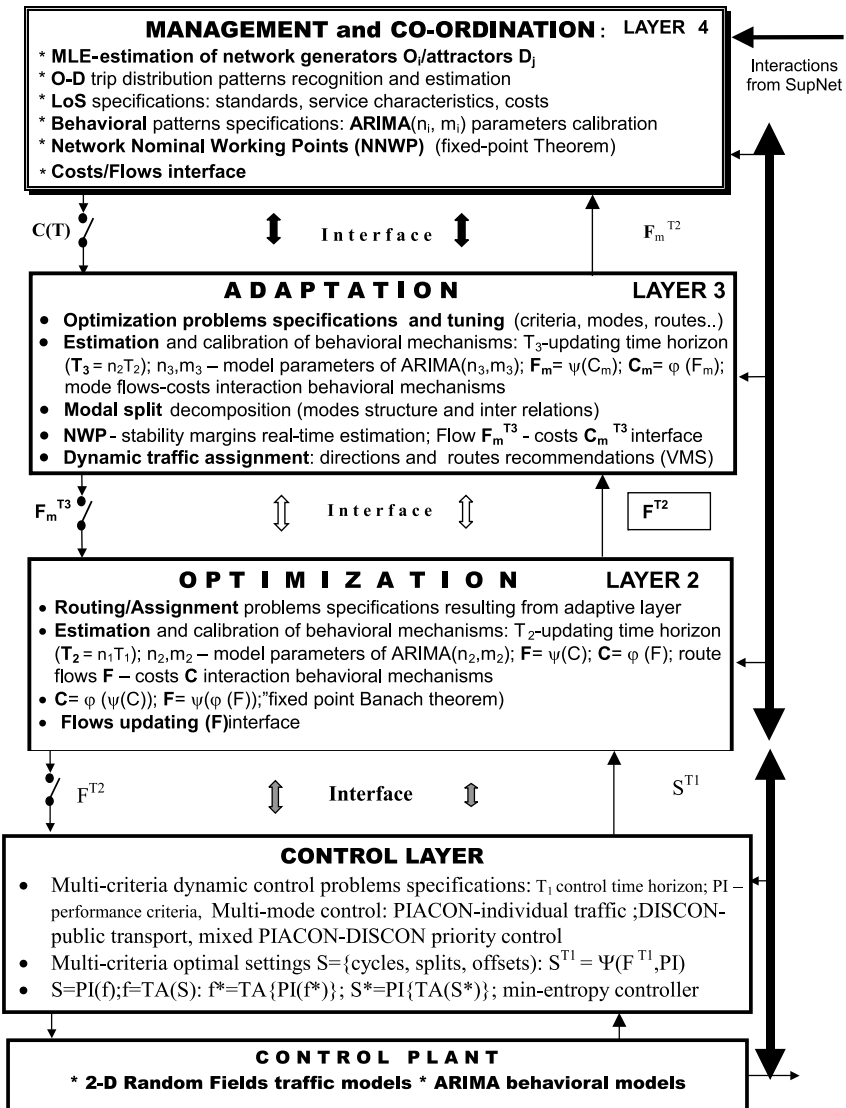


Fig. 1. Interactive ITS system multi-layer functional structure

The behavioural user-oriented interactions are both layer and entropy-compatible and have real-time on-line estimated parameters: T_i – reaction horizon; n_i/m_i – behavioural patterns. This offer completely new dynamic asynchronous network-wide behavioural model that is compatible to real transportation system behaviour observations. The starting point for upper layers interactions interface may be the following distribution and modal split multi-criteria problem:

$$PO_{\min} T_{ij} T_{ij}^m : Q(T) = \{Q_i; i = 1 \dots 3\}$$

$$\sum_j T_{ij} = O_i \quad \sum_i T_{ij} = D_j \quad T_{ij} = \sum_m T_{ij}^m$$

where:

$$Q_1 = \sum_m \sum_i \sum_j T_{ij}^m c_{ij}^m \quad Q_2 = \sum_i \sum_j T_{ij} (\ln T_{ij} - 1)$$

$$Q_3 = \sum_m \sum_i \sum_j T_{ij}^m (\ln T_{ij}^m - 1) - Q_2$$

This initial problem may be solved by determination of the compromise set between the criteria but the behavioural mechanism will influence the compromise set specifications (e.g. shape, parameterisation). Of course there are possible different modal split structures (e.g. nested or mixed modes) that increases the number of criteria (Cea *et al.* 2008). The starting point for medium layers will be a multi-objective combined distribution and assignment problem with additional network arcs $a \in A$ related criterion $Q_4 = \sum_a c(f_a)$ and corresponding conservation laws for routes $r \in R$ and arc flows; $f_a = \sum_r T^r \delta_{ar}$ (δ_{ar} Kronecker delta) and $T_{ij} = \sum_r T_{ij}^r$. At the bottom control layer the multi-criteria PIACON control problems will be solved (Adamski 1983, 2005, 2006).

2. ITS Bottom Direct Control Layer

The simple entropy related control idea can be related with the detection zone which consists of a stretch of road of a given length $L[m]$. The spatial distribution of n detected vehicles is represented by a set of inter-vehicle spacing values $\{s_i\}^n$ treated as realizations of a random variable. It is known that the entropy H reach maximum H_{\max} /minimum H_{\min} values for respectively uniform /cluster (e.g. as platoon of vehicles) spacing distributions. Therefore the entropy $H \in [H_{\min}, H_{\max}]$ under the stationary traffic conditions or entropy parameter $HP \in [0, 1]$ after interval normalization, $HP = (H_{\max} - H)/(H_{\max} - H_{\min})$, may be treated as a measure of smoothness of the traffic flow, which is increasing/decreasing with the spacing uniformity/ bunching over a road section. The simple intelligent real-time traffic signals control logic may be as follows (Adamski 1995, 1996, 1997, 2002, 2003, 2006, 2007, Adamski Florek 1997). In the first prediction stage after the assignment of the minimum green time for the traffic signals, the entropy parameter HP is estimated and for every Δt time interval utilized to prediction of the traffic volume q_{pr} (e.g. by the formula of $q_{pr} = KV_f(1 - K/K_j)HP$; where V_f – free flow speed, K, K_j – density and jam density, respectively). In the second decision-making stage the green signal is extended on the threshold

value or ended by a maximum green time constraint according to the following decisive equation: $q = q_{pr} - w/(g_{max} - g)^2$, where: w – weighting coefficient; g, g_{max} – current and maximal green times. The results from the simple engineering models (Adamski Florek 1999) show that the maximum efficiency of the proposed control method corresponds to the situations of the cycle time and green split readjustments according to traffic arrival fluctuations. Nevertheless, even in the case of fixed cycle time, entropy control can reduce the average delays by about 25% , the average queue length by 20 to 60% depending on the traffic flow (see Tab. 1).

Table 1

Example of most congested intersection Czarnowiejska Str.-Mickiewicz Av. in Cracow

		A	B	C	D	
	Average delay /vehicle [s]	21.82	15.16	12.12	10.53	
	Average number of stops /vehicle	0.73	0.67	0.78	0.70	
	Average queue length for group (vehicles)	1	15.68	11.39	8.85	6.48
		2	13.52	6.36	7.35	6.25
		3	6.15	4.21	3.62	3.20
		4	8.10	5.44	4.17	4.14
5		5.95	2.46	3.41	3.20	
6		7.45	3.73	3.66	3.51	

* Comparison of control methods: fixed $C^* = 90(\text{sec})$ / C variable cycle time: A – Existing, with C^* , B – Entropy control with C^* ; C – Delays control with C, D – Entropy control with C

For the more sophisticated minimum entropy control method, the bi-criteria controller offering trade-offs between the H^∞ and LQG solution is proposed. The signal plan for that intersection consists of six signal groups controlled in three phases, thus we have six state variables and three control variables. The information about the number of vehicles on approaches to the intersection, which forms a state vector in our formulation, was supplied by the Krakow video-detectors data. By applying the minimum entropy controller we can obtain a pre-specified level of robustness and good performance associated with the LQG control problem (see Fig. 2). From applications point of view the solutions from the middle of the non-dominated set of trade-offs $H^\infty - LQG$ are recommended, because then a performance is close to that obtained from the LQG problem, and a satisfactory level of robustness is guaranteed.

The PIACON multi-criteria traffic control method generates more complicated interactions between layers offering different service options for different traffic flows at intersection. The PIACON structure of preferences may be influenced from the upper layers from the point of view of network operational specifications.

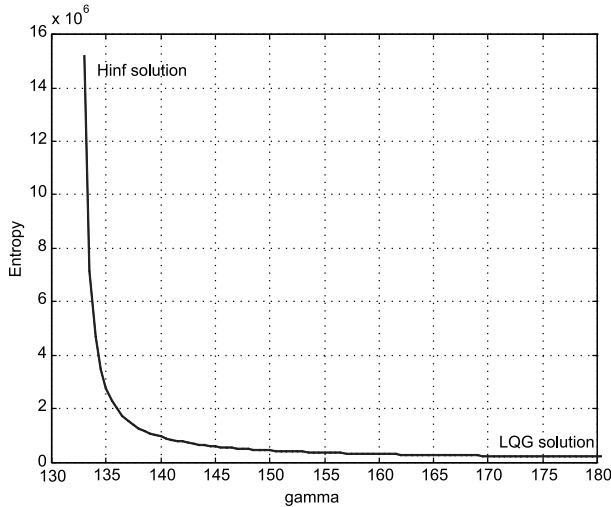


Fig. 2. Entropy as a trade-off between H^∞ and LQG solutions

3. Structure of control preferences

To reduce the influence of the subjectivity and evaluate the objective weight of each control criteria in a given traffic situation, the AHP-Entropy method was used and the ranking was realized according to calculated distance d_2 and close-degree to the ideal point. There are eight control performance criteria (C1–C8) to be evaluated: the number of stops, delays, capacity, queues, discomfort measures, priorities, dedicated modes, flexibility degree. These criteria to be evaluated by six traffic situations markers (M1–M6) representing traffic flow conditions and operational events such as traffic events blockings, operational priorities and network synchronization requirements: free flow, near capacity, over-saturated, blockings, priorities, “synchro”. The proposed approach consists of 5 steps (see Tabs 2 and 3):

- A. Standardize the TSM (Traffic Situations Markers) and determine target matrix.
- B. Determine the entropy indicator weight λ_e for TSM.
- C. Calculate the weights from AHP and combine with λ_e to get the comprehensive weight WW.
- D. Construct the normalized matrix to determine the ideal point.
- E. Calculate the distance d_2 and close degree to the ideal point to sort control criteria in the preference structure.

Table 2
SP – Free flow conditions

Advanced AHP-Entropy						WW
1.0000	2.0000	5.0000	7.0000	2.0000	1.0000	0.3330
0.5000	1.0000	3.0000	5.0000	2.0000	1.0000	0.2158
0.2000	0.3333	1.0000	5.0000	1.0000	2.0000	0.1473
0.1429	0.2000	0.2000	1.0000	3.0000	2.0000	0.0969
0.5000	0.5000	1.0000	0.3333	1.0000	1.0000	0.0889
1.0000	1.0000	0.5000	0.5000	1.0000	1.0000	0.1181
$\lambda_{\max} = 6.4339$		CI = 0.02868		CR = 0.02313		
$\lambda_e =$	0.3915	0.1490	0.1985	0.1252	0.0696	0.0663

Table 3
Preference structure

C – criteria	d2	Ranking	Close-degree	Ranking
C1	0.2814	2	0.3397	1
C2	0.2611	1	0.4376	2
C3	0.2952	3	0.5646	3
C4	0.4048	6	0.6041	6
C5	0.4045	8	0.6530	8
C6	0.3212	7	0.7098	5
C7	0.4013	5	0.7562	4
C8	0.3230	4	0.7909	7

4. Application example

In order to illustrate the combined distribution-modal split-assignment-control problem consider a simple road network $G = (N, A)$ with nine nodes and twelve links as shown in Figure 3. Trips are generated at nodes $O_1 = 500 \text{ trips/h}$ and $O_2 = 350 \text{ trips/h}$ and they are attracted by nodes $D_1 = 400 \text{ trips/h}$ and $D_2 = 450 \text{ trips/h}$. Signal controllers are located at nodes C_1 , C_2 and C_3 . There are two modes operating over this network: individual (cars) and public (buses). The effects of congestion due to the limited capacity of road network and public transport vehicles and delay due to signal control are directly considered. Table 4 shows the main parameters for the link cost functions of the road network and Table 5 presents itineraries of the public transport lines.

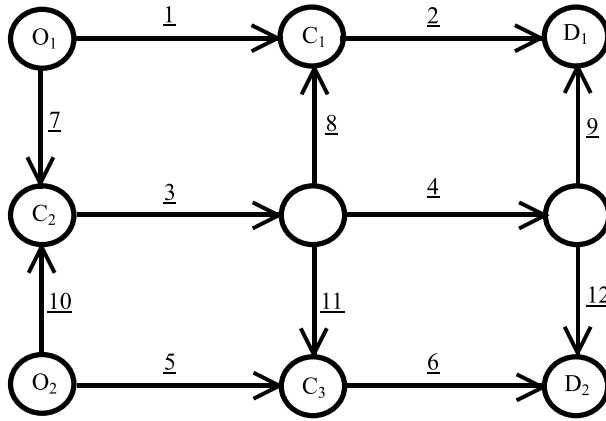


Fig. 3. Road network $G = (N, A)$

Table 4
Parameters for link cost function

Link	1	2	3	4	5	6	7	8	9	10	11	12
Free flow travel time [min]	11.5	12.2	4.8	7.2	10.2	12.5	2.5	2.0	3.2	1.8	2.0	2.5
Capacity [veh]	50	50	150	150	50	50	110	50	50	90	50	80
Fixed flow [veh/h]	4	4	8	4	4	8	4	0	4	4	4	4

Table 5
Itineraries of the public transport lines

Line	Itinerary
1	1-2
2	7-3-11-6
3	10-3-4-9
4	5-6

The problem was solved as a bi-level optimization model: at a higher level the combined distribution-modal split-assignment problem was solved, while at the lower – a poly-optimal signal control (PIACON) procedure at three mentioned above intersections (nodes) was adopted. The first model is in a fact multi-criteria optimization problem, so a compromise set of solutions could be determined, for example a trade-off between costs and modal split (Fig. 4) and then one can choose a specific non-dominated solution.

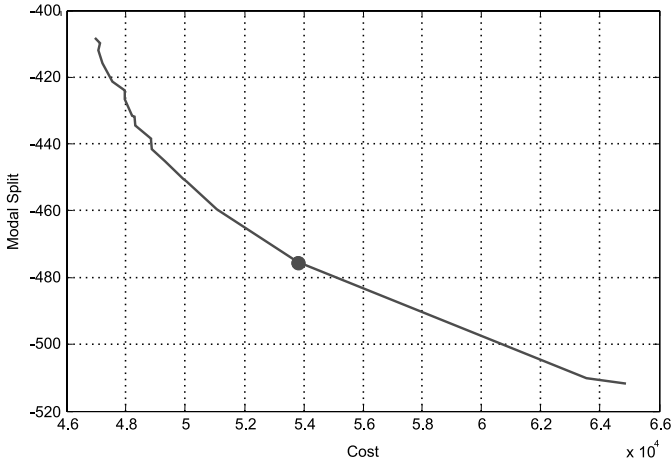


Fig. 4. Compromise set cost-modal split

Users choose their routes according to Wardrop's first principle, so changes in travel time due to signal control can cause a switch to alternative paths. On the other hand changes in link flows causes changes in traffic signals, but in the static case considered at the higher level, this procedure converges very quickly.

Table 6 shows flows on all paths in the network for the selected non-dominated solution; as can be seen individual users choose only routes with minimal cost (travel time), which prove that users behave according to User Equilibrium solution. In Table 7 trip matrices are presented.

Table 6
Equilibrium flow

OD	Path	Flow [veh/h]	Cost [min]
O ₁ D ₁	1-2	29.63	29.01
	7-3-4-9	35.38	29.01
	7-3-8-2	0.00	30.03
O ₁ D ₂	7-3-4-12	68.14	29.37
	7-3-11-6	0.00	29.65
O ₂ D ₁	10-3-4-9	3.39	26.30
	10-3-8-2	0.00	27.01
O ₂ D ₂	5-6	23.41	26.15
	10-3-4-12	18.04	26.15
	10-3-11-6	0.00	26.64

Table 7
OD matrices

Car [pass/h]			Bus [pass/h]			Total [pass/h]		
	D ₁	D ₂		D ₁	D ₂		D ₁	D ₂
O ₁	65.02	68.20	O ₁	185.01	181.77	O ₁	250.03	249.97
O ₂	3.39	41.46	O ₂	146.58	158.57	O ₂	149.97	200.03

5. Conclusions

The inter-layers users behavioural interactions in a crucial way determines the features of the whole system operation and control actions in particular. In this paper the real-time control preference structures recognition based on network interaction structure with the exploration of three main interfaces between system layers was presented. In multi-criteria control actions these interfaces guarantee first of all the stable operation of the whole system as well as the effective operation of individual layers. The dynamical behavioural interactions are, in general, very complex due to many uncertain and not directly measurable premises. The entropy compatibility on all system layers of the proposed solution was illustrated. The special operational flexibility was presented at control layer where several multi-criteria options can be used in a real-time recognized system-oriented mode. The main conclusion may be formulated that above problems to a high degree are enabling solutions for advanced ITS system operations.

References

- Adamski A. 1983, *Optimal Dispatching Control of Bus Lines*. Proc 4th IFAC/IFIP/IFOR S Inter. Conf. on CONTROL in TRANSPORTATION SYSTEMS, Baden-Baden 67–72
- Adamski A. 1992, *Probabilistic models of passengers service processes at bus stops*. Transportation Research B, 26, pp. 253–259.
- Adamski A. 1992, *Application of Neural Network Models to Optimal Traffic Control in Urban Networks*. In: Gartner N.G., Improta G., eds. URBAN TRAFFIC NETWORKS, COMPENDIUM 2, pp. 841–857.
- Adamski A. 1993, *Optimal Adaptive Dispatching Control in an Integrated Public Transport Management System*. 2nd EURO WG Conf. INRETS ACTES 917–938. 1993
- Adamski A. 1995, *Multicriteria Traffic Control with Video Feedback*. Proc. 4-th AATT Conference, Eds. Y. J. Stephanedes, F. Filippi, ASCE Publ., pp.620–627.1995
- Adamski A. 1995, *Real-time computer-aided control in public transport from the point of view of schedule reliability*. Lecture Notes in Economics and Mathematics 430, 23–38,
- Adamski A. 1996, *Flexible Dispatching Control Tools in Public Transport*. In Advanced Methods in Transportation Analysis eds. L Bianco, P Toth, Springer 1996, 481–506
- Adamski A. 1996, *Multi-criteria Traffic Control with Video Feedback*. Applications of Advanced Technologies in Transportation Engineering. Eds. Y.J. Stephanedes, F. Filippi. ASCE Publications. pp. 620–627.

- Adamski A. 1997, *REALBAND- Real-time traffic movement coordinating along an arterial using data from video-detector*. AUTOMATICS, vol. 2
- Adamski A., K. Florek 1997, *TEDMAN System Analysis Approach for Traffic Control on a Signalized Junctions*. AUTOMATICS, vol. 1 , pp. 286–298.
- Adamski A. 1998, *PIACON: Traffic Control Method with Video Feedback*. AATT Conference Eds. Chris T. Chendrickson, S. Ritchie, ASCE Publ. 1801, pp.217–224. 1998
- Adamski A. 1999, *Integrated Transportation Systems. Modeling and Management in Transportation* EURO WG on Transportation vol. 1, pp. 21–34, 1999.
- Adamski A., Florek K. 1999, *Minimum Entropy Traffic Control with video-detectors feedback*. Proc. Int. Conference on Modeling and Management in Transportation Eds. A. Adamski, A. Rudnicki, J. Zak) vol.2. pp. 85–92, Poznań-Kraków 1999.
- Adamski A. 2002, *ITS: Integrated Transportation Systems*. Archives of Transport Quarterly, Polish Academy of Science, vol. 14, issue 2, pp. 5–22, 2002.
- Adamski A. 2002, *Intelligent Integrated Transportation Systems*. 9-th Meeting of the EURO WG Inter-modality, Sustainability and ITS, Bari, 565–570, 2002.
- Adamski A. 2003, *ITS: Management, Surveillance and Control*. Monograph: AGH University Scientific Publications, 2003, Krakow.
- Adamski A. 2005, *PIACON-DISCON integrated approach to public transport priority control at traffic signals.*, pp. 417–422, Advanced OR and AI Methods in Transportation, Publishing House Poznan University of Technology, 2005.
- Adamski A. 2006a, *PIACON: Robust vehicle trajectory based arterial multi-criteria traffic signal control*. Extra EURO Conf. on Handling Uncertainty in Transport Bari 608–615.
- Adamski A. 2006b, *Integrated traffic management, surveillance and control systems in urban areas*. TiBT06 Transport Telematics and Safety, pp. 104–112, 2006
- Adamski A. 2006c, *IILS: Integrated Intelligent Logistics Systems*, Krakow University of Technology Logistics Conference, pp.25–38, 2006.
- Adamski A. 2007, *Intelligent anticipative dispatching control system in public transport*. Monograph: Transactions on Transport Systems Telematics: Modelling, Management and Image Processing, pp. 70–75. Silesian University Press
- Cantarella G.E. 1993, *Day to day dynamics in transportation networks stability and limits of equilibrium in two-link network* Sistemi Urbani 1 , pp. 27–50
- J Cea, J. Fernandez, L Grange 2008, *Combined Models with Hierarchical Demand Choices: A Multi-Objective Entropy Optimisation Approach*, Transport Reviews, vol. 28, no. 4. 415–438
- Meneguzzo C. 1997, *Review of models combining traffic assignment and signal control* Journal of Transport Eng. 123–2, pp.148–155.
- Meneguzzo C. 2011, *Dynamic process models of combined traffic assignment and control with different signal updating strategies* ibid (to appear)