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Equivalent Noise Level and Traffic Lights Arterial Optimization*

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1. Introduction

Traffic noise pollution is a main source of air pollution in intensive urban areas [5]. The purpose of this research is not only monitoring the pollution but to take measures to reduce it using appropriate control strategy as well. Here the acoustic noise level is introduced as an integral parameter which assesses the vehicle emissions. From technical point of view the acoustic measurements do not need a complex technical and hardware support. The control of the green duration of the traffic lights is performed by appropriate noise measurements.

The problem of controlling the traffic lights is considered as a necessary step for the dynamical traffic flow control [1, 21]. The optimal duration of the traffic lights is done by means of minimization of the queue lenght at oversaturated traffic junction [12, 13, 3]. The queue lenghts are state variables which have to be minimized according to the optimal time duration of the green light. The variables which have to be measured are the density of the input stream (vehicles per hour) and the initial queue lenght at the intersection (vehicles). The traffic flow measurements are performed by inductive loops [19, 25] situated closed to the junction. More sophisticated and expensive way is to implement image processing and software identification tools for real time automatic flow measurements [27].

To obtain the intensity of the input traffic and to evaluate the initial queue lenghts in front of the junction is a problem connected with a complex and expensive technical support. Here the equivalent noise level is introduced as a state variable which can be measured for the evaluation of the queue lenghts and traffic intensity. The noise level as an integal characteristic is easy to obtain without cost valuable technical support. Additionaly, the appropriate optimal control on the traffic lights will decrease the noise pollution.

In this work to reduce the pollution a model of traffic queues at connected crossroad sections are proposed. The relation between green and red light of the traffic signals at a single cross-road section is used as a control variable. An optimization problem is

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proposed. This control policy decreases the trafic's queue and respectively the noise pollution.

2. Case study

In fact the traffic noise is continuously fluctuating but for a short period of time it is considered as a constant value. In a case of a straight section of road the equivalent noise level L_{eq} due to the passing of a series of vehicles over a period of time $[t_1\ t_2]$ is given by the integral [20, 4]

(1) $$L_{eq} = 10 \log \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} Q \frac{p_i^2(t)}{p_0^2}\, dt\ ,$$

where Q is the number of vehicles passed trough the road section for the time period $(t_2 - t_1)$; $p()$ and p_0 – the acoustic and the reference pressure level. If the traffic is steady L_{eq} is no longer dependent on the duration of the measurements so the relation (1) tends to the integral form [28]:

(2) $$L_{eq} = L_{eqi} + 10 \log Q, \quad L_{eqi} = 43 \text{ dB}.$$

For different noise sources L_{eqi}, $i = \overline{1, n}$, the equivalent noise level L_{eq} is a logarithmic function of the components L_{eqi} [28], given by

(3) $$L_{eq} = 10 \log \sum_{i=1}^{n} 10^{0,1 L_{eqi}}\ .$$

Relations (2) and (3) are introduced in an optimization problem according to the traffic noise measurement scheme consisting two control and measurement points A and B, situated closed to the traffic junction, Fig.1.

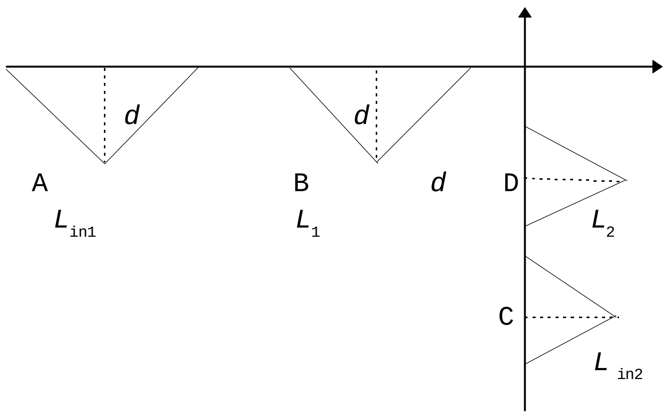

Fig.1. One way intersection measuring scheme

The points A and C are situated distantly to the junction which tasks are to estimate the intensities of the input traffic streams to the horizontal and vertical traffic flows. The points B and D are situated close to the junction and estimate the noise of the waiting vehicles. Two noise equilibrium equations are written for points B and D. All noise measurements are performed at a distance d from the street.

The noise equilibrium at point B consists of three main noise sources arising from:

- the queue of vehicles waiting for green signal, $L_{eq}^{B} = L_1$;
- the input traffic stream $L_{eq}^{A} = L_{in1}$;
- the output traffic flow decreasing the waiting queue during the green signal L_{out}.

The equivalent noise level at point B constituted from these three independent noise sources, according to (3), is written by the relation

$$L_1(k+1) = 10 \log \left[10^{0,1L_1(k)} + 10^{0,1L_{in1}(k)} - 10^{0,1L_{out}(k)} \right],$$

where k is the discrete time.

The value of L_{out} can be expressed by (1) as

$$L_{out} = L_{eqi} + 10 \log Q.$$

The value Q means the number of vehicles which will pass the intersection during the green signal. It can be expressed as

$$Q(k) = s_1 u(k),$$

where s_1 is the maximum number of vehicles which is possible to leave the intersection in the horizontal way during one cycle $\boldsymbol{c}$ of the traffic lights; $u(k)$ is the relative duration of the green light expressed as a part of the total cycle $\boldsymbol{c}$

$$c = \bar{u}_{green} + \bar{u}_{red} + \bar{u}_{amber}, \tag{4}$$

$$u = \bar{u}_{green} / c,$$

$\bar{u}(\,)$ – the duration of appropriate traffic signal.

After substituting L_{out} in $L_1(k+1)$ the noise equilibrium at point B is written by the equation

$$L_1(k+1) = 10 \log \left[10^{0,1L_1(k)} + 10^{0,1L_{in1}(k)} - 10^{0,1(L_{eqi} + 10 \log s_1 u(k))} \right]. \tag{5}$$

Similar consideration derives the noise equilibrium at point D as

$$L_2(k+1) = 10 \log \left[10^{0,1L_2(k)} + 10^{0,1L_{in2}(k)} - 10^{0,1(L_{eqi} + 10 \log s_2 (0,9 - u(k)))} \right], \tag{6}$$

where $L_2(\,)$ is the equivalent noise level at point D for two consequent time discretes k and $k+1$; L_{in2} is the noise, resulting from the input traffic for the vertical axis, s_2 – the maximum number of vehicles which can leave the junction for one cycle in a vertical direction, $0.9 - u$ is the green light duration assuming that the amber light is $0.1c$ in (4).

Relations (5) and (6) are applied in an optimization problem which will minimize the noise behaviour of the junction. The goal function J_1 of this optimization problem is given engineering meaning of equivalent noise level arising from the two noise sources at points B and D. Thus, the minimization of J_1 will get a desirable reduction of the noise behaviour of the junction. The general consideration of the optimization theory impose on the components of J to be chosen in a quadratic form. These considerations motivate the form of J applied in this research as

$$J_1 = 10 \log \sum_{k=1}^{k_p} \left[(10^{0.1L_1(k+1)})^2 + (10^{0.1L_2(k+1)})^2 + (u(k))^2 \right]. \tag{7}$$

The extremum point u^* is evaluated from the first derivative of J_1

$$\min J_1(u) \Rightarrow u^* = \arg\,[dJ_1/du = 0]$$

or

(8) $$u^* = \frac{\alpha s_1 + \beta s_2}{s_1^2 + s_2^2 + 1}.$$

The solution (8) is obtained in an analytical form which allows to perform closed loop control of the traffic signals in real time. The input data for the control law (8) is the current values of the noise levels $L_1(0)$, $L_2(0)$, L_{in1} and L_{in2}. During the cycle **c** these values are measured continuously. In the end of the cycle the mean values of $L_1(0)$, $L_2(0)$, L_{in1} and L_{in2} are substituted in (8) and the optimal duration u^* is applied for the next cycle of the traffic signals. This control policy evaluates permanently the green signal for every traffic cycle.

3. Noise modeling of arterial street with intersections

The noise equilibrium model is extended for joint connected intersections with an arterial direction. Two junctions on a main street constitute a traffic network which endure prolonged congestions in the downtown of Sofia. The oversaturated traffic network consists of two neighbour junctions with estimated traffic loads given in Fig.2.

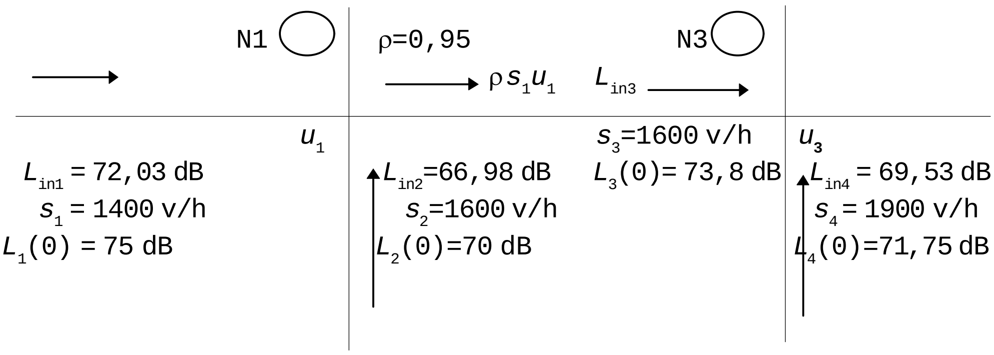

Fig.2. Traffic network scheme

The traffic control of this network must assure smooth traffic motion from left to right direction without rising the vehicle queues in front of the two junctions despite the interruptions done by the traffic signals allowing the vertical traffic flows. The main traffic load arises from the vehicles passing trough the horizontal axis, starting from intersection N1 and continueing to intersection N3. This occasion gives reason to assume that the input traffic flow for intersection N3 is constituted by the volumes $\rho s_1 u_1$, where the coefficient $\rho = 0.95$ is determined by statistical considerations.

The noise equilibrium model (5) was applied for the case of arterially connected intersections. The control arguments are the relative green durations u_1 and u_3, respectively for both intersections. The estimation of the feasible areas of variation for the controls u_1 and u_3 is performed as follows:

Intersection N1

· The input traffic noise of the horizontal axis must be less than the output one during the green phase of the traffic signals

$$L_{in2} = 10 \log 10^{0,1L_{in1}} \leq 10 \log s_1 u_1 10^{0,1L_{eqi}} \quad \text{or} \quad u_1 \geq 10^{0,1(L_{in1}-L_{eqi})} / s_1 = 0,57.$$

· The input traffic noise of the vertical axis must be less than the output one :

$$L_{in2} = 10 \log 10^{0,1L_{in2}} \leq 10 \log s_2(0,9 - u_1) 10^{0,1L_{eqi}} \quad \text{or} \quad u_1 \leq 0,9 - 10^{0,1(L_{in1}-L_{eqi})} / s_2 = 0,74$$

Both these constraints limit the feasible region of u_1

(9) $$0,57 \leq u_1 \leq 0,74.$$

Intersection N3

The input traffic noise for the horizontal direction must be less than the output one during the green phase u_3

$$L_{in3} = 10 \log [\rho s_1 u_1 10^{0.1L_{eqi}}] \leq 10 \log(s_3 u_3 10^{0.1L_{eqi}}).$$

In this relation the value of u_1 must be substituted with its worst case which is the maximal duration of u_1. This value is given from (9) as

$$u_1^{max} = 0,9 - 10^{0.1(L_{in2}-L_{eqi})} / s_2.$$

After rearanging the lower boundary of u_3 is obtained analytically:

$$u_3 \geq \rho\, s_1 / s_3 (0,9 - 10^{0.1(L_{in2}-L_{eqi})} / s_2) = 0,62.$$

From analytical considerations concerning the noise feasible equilibrium for the vertical axis of junction N3, the relation is

$$L_{in4} \leq 10 \log[s_4(0,9 - u_3) 10^{0.1L_{eqi}}] \quad \text{or} \quad u_3 \leq 0.9 - 10^{0.1(L_{in4}-L_{eqi})} / s_4 = 0,66,$$

(10) $$0,62 \leq u_3 \leq 0,66 .$$

Relations (9) and (10) determine the feasible area of control variations. The noise equilibrium equations written for the junctions are given by:

· junction N1, horizontal axis:

$$L_1(1) = 10 \log[10^{0,1L_1(0)} + 10^{0,1L_{in2}} - s_1 u_1 10^{0,1L_{eqi}}];$$

· junction N1, vertical axis

$$L_2(1) = 10 \log[10^{0,1L_2(0)} + 10^{0,1L_{in2}} - s_2 (0,9 - u_1) 10^{0,1L_{eqi}}];$$

· junction N3, horizontal axis:

$$L_3(1) = 10 \log[10^{0,1L_3(0)} + 10^{0,1L_{in3}} - s_3 u_3) 10^{0,1L_{eqi}}],$$

where $L_{in3} = \rho u_1 s_1 10^{0.1L_{in2}}$;

· junction N3, vertical axis:

$$L_4(1) = 10 \log[10^{0,1L_4(0)} + 10^{0,1L_{in4}} - s_4 (0,9 - u_3) 10^{0,1L_{eqi}}].$$

The goal function of the optimization problem gives the engineering meaning of the equivalent noise level, produced by the multiple noise sources

(11) $$J = 10 \log\{(10^{0,1L_1(1)})^2 + (10^{0,1L_2(1)})^2 + (10^{0,1L_1(3)})^2 + (10^{0,1L_4(1)})^2 + (u_1 10^{0,1L_{eqi}})^2 + (u_3 10^{0,1L_{eqi}})^2\} .$$

Hence the optimization problem concerning the traffic network is

$$\min_{\substack{u_1\ u_3\\ L_1\ L_2\ L_3\ L_4}} J \tag{12}$$

$$L_1(1) = L_{\mathrm{eq}i} + 10\log(\alpha_1 - s_1 u_1),$$

$$L_2(1) = L_{\mathrm{eq}i} + 10\log(-\beta_1 + s_2 u_1),$$

$$L_3(1) = L_{\mathrm{eq}i} + 10\log(\alpha_3 + \rho s_1 u_1 - s_3 u_3),$$

$$L_4(1) = L_{\mathrm{eq}i} + 10\log(-\beta_3 + s_4 u_3),$$

$$0{,}57 \le u_1 \le 0{,}74\,; \qquad 0{,}62 \le u_3 \le 0{,}66\,,$$

where

$$\alpha_1 = 10^{0,1\,(L_1(0)-L_{\mathrm{eq}i})} + 10^{0,1\,(L_{\mathrm{in}1}-L_{\mathrm{eq}i})},$$

$$-\beta_1 = 10^{0,1\,(L_2(0)-L_{\mathrm{eq}i})} + 10^{0,1\,(L_{\mathrm{in}2}-L_{\mathrm{eq}i})} - 0{,}9\,s_2\,,$$

$$\alpha_3 = 10^{0,1\,(L_3(0)-L_{\mathrm{eq}i})}\,,$$

$$-\beta_4 = 10^{0,1\,(L_4(0)-L_{\mathrm{eq}i})} + 10^{0,1\,(L_{\mathrm{in}4}-L_{\mathrm{eq}i})} - 0.9\,s_4.$$

The solution of this constrained problem (12) is found by substituting $L_i(1)$, i=1,4 in J and then the minimum of J is calculated in regard to the boundaries (9) and (10). Analytical solutions of the optimization problem (12) can be found by the system equations

$$u^*_1 = \arg\{dJ/du_1 = 0\} \quad \text{and} \quad u^*_3 = \arg\{dJ/du_3 = 0\}.$$

After a few algebraic operations the values u and u are expressed in a determinant form

$$u^*_1 = D_1 / D, \qquad u^*_3 = D_3 / D, \tag{13}$$

where

$$D = \begin{vmatrix} s_1^2(1+\rho^2) + s_2^2 + 1 & -\rho\, s_1 s_3 \\ -\rho\, s_1 s_3 & s_3^2 + s_4^2 + 1 \end{vmatrix},$$

$$D_1 = \begin{vmatrix} \alpha_1 s_1 + \beta_1 s_2 - \rho\alpha_3 s_3 & -\rho\, s_1 s_3 \\ \alpha_3 s_3 + \beta_3 s_4 & s_3^2 + s_4^2 + 1 \end{vmatrix},$$

$$D_3 = \begin{vmatrix} s_1^2(1+\rho^2) + s_2^2 + 1 & \alpha_1 s_1 + \beta_1 s_2 - \rho\, s_1 s_3 \\ -\rho\, s_1 s_3 & \alpha_3 s_3 + \beta_3 s_4 \end{vmatrix}.$$

Applying relations (13) and the constraints (9) and (10) the solution of the constrained optimization problem (12) it is obtained in an analytical form

$$u^0_1 = \begin{cases} u^*_1 \text{ if } 0{,}57 \le u^*_1 \le 0{,}74 \\ 0{,}57 \text{ if } u^*_1 \le 0{,}57 \\ 0{,}74 \text{ if } u^*_1 > 0{,}74 \end{cases}; \qquad u^0_3 = \begin{cases} u^*_3 \text{ if } 0{,}62 \le u^*_3 \le 0{,}66 \\ 0{,}62 \text{ if } u^*_3 \le 0{,}62 \\ 0{,}66 \text{ if } u^*_3 > 0{,}66\,. \end{cases} \tag{14}$$

The analytical relations (13) allow the control algorithm to be implemented in a closed loop. The control system continuously performs data acquisition for the input noise L_{in} and the resulting noises in front of the junctions $L(0)$. The appropriate green signal

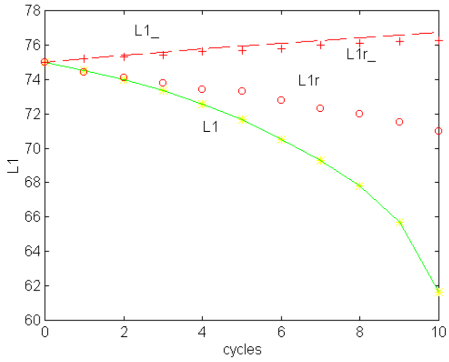

Fig.3. Intersection 1: horizontal flows

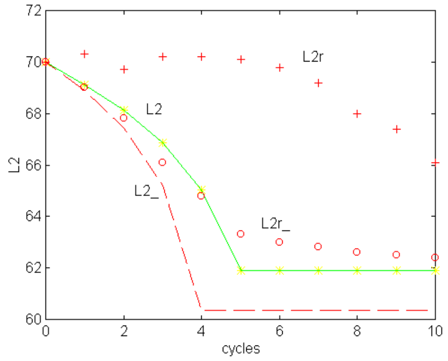

Fig.4. Intersection 1: vertical flows

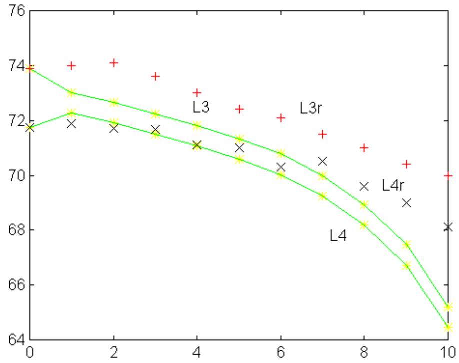

Fig.5. Intersection 3: horizontal and vertical flows

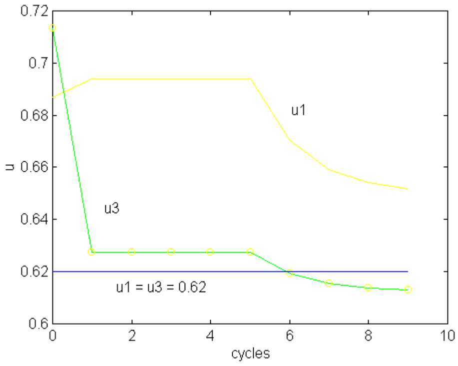

Fig.6. Green signals of intersections 1 and 3

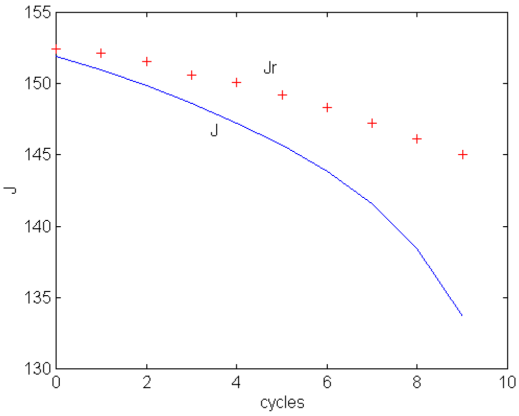

Fig.7. Traffic network: goal function

durations will be evaluated according to the control law (14) and implemented for every cycle of the traffic lights.

Relations (13)–(14) were applied in a simulation procedure for a sequence of traffic cycles. The resulting controls and the behaviour of the noise levels are given in Fig. 3, 4, 5, 6 and 7. To compare the simulation result with practical implementation the calculated sequence of u^0_1 and u^0_3 of the simulation were applied for both traffic junctions. The estimated noise behaviour is noted as L_{ir}, $i=\overline{1,4}$. Due to the limited number of available sound exposer meters (only two), the resulting equivalent noise levels were measured two by two. It means that for one day applying u^0_1 and u^0_3 only $L_1(1)$ and $L_2(1)$ is measured. The next day the experiments of applying the sequence u^0_1 and u^0_3 were repeated but measurements were done for $L_3(1)$ and $L_4(1)$. This noninstantaneous technology of data acquisition yields additional data inaccuracy. Despite this nonprecise treatment of the control scheme, the real process keeps decreasing characters of all noise levels L_i, $i=\overline{1,4}$, which benefits the application of the noise equilibrium modeling in real time implementation.

4. Conclusions

This work applies acoustic measurements to the optimal control of traffic signals. The acoustic measurements are connected in a close loop form to the control process which adapts the optimal solutions to the nonstationary traffic conditions. Due to the correlations between the acoustic noise and the vehicles exhaustions, this control problem introduces explicitly the environmental pollution considerations. The development of control algorithms for a set of simply connected urban junctions intersections operating by acoustic measurements influences positively the environmental pollution in urban areas.

References

1. Al-Khalil. An urban traffic control: a general approach. – In: Transactions on Systems, Man and Cybernetics. Vol. SMC–15, 1985, No 2.
2. Abramzuk, T. Image processing technique applied to traffic measurement. – In: Control, Computers, Communications in Transportation. IFAC Symposium CCCT'89, Paris, France, 1989, 77–81.
3. Barriere, J., J. Farge, J. Henry. Decentralization hierarchy in optimal traffic control. – In: 5th IFAC/IFIP/IFORS Conference on Control in Transportation Systems, Vienna, Austria, 1986, 209-214.
4. Beruard, B. Environmental noise measurements. – Techn. Review No 1, Bruel&Kjaer, 40, 1986.
5. Blosseville, J. Titan. New traffic measurement by image processing.– In: Control, Computers, Communications in Transportation.– In: IFAC Symposium CCCT'89, Paris, France, 1989, 69-73.
6. Bresse, B., A. Mocheoine. Traffic management, energy and pollution.–Recherche, Transports, Securite, 1990, No 6, 119–124.
7. Cremer, M. Flow variables: Estimation. Concise Encyclopedia of Traffic and Transportation Systems. (M.Papageorgiou ed.). New York, Pergamon Press, 1989, 143–148.
8. Gazis, D. The traffic control – theory and application. – In: D.C.Gazis ed., Traffic Science. N.York, London, Sydney, Toronto, Wiley Interscience, 1974, 209–229.
9. Grau, R., J. Barcelo. CARS: An experience in demand-responsive traffic control.– In: Proceedings of 1st Meeting of the Euro Working Group in Urban Traffic and Transportation, Landshut, Technical University of Munich, Germany, 1992.
10. Henry, J., J. Farges. Traffic congestion control.– In: Control, Computers, Communications in Transportation. IFAC Symposium CCCT'89, Paris, France, 1989, 257–261.
11. Kim, K., M. Bell. Development of integrated traffic control strategy both in urban signalized and motorway networks. – In: Proceedings of 1st Meeting of the Euroworking Group in Urban Traffic and transportation, Landshut, Technical University of Munich, Germany, 1992.
12. Lim, J., S. Nwang, I. Suh, Z. Bien. Hierarchical optimal control of oversaturated urban traffic networks. – Int.J. of Control, **33**, 1981, No 4, 727–737.
13. Lopat in, A. Modeling the Traffic Load Process and Urban Vehicle Sheduling. Moscow, Transport, 1985 (in Russian).
14. Messmer, A., M. Papageorgiou . Automatic control methods applied to freeway network traffic. – In: 12th IFAC World Congress, Australia, vol.9, 1983, 233–238.
15. Michalopoulos, P., G. Stephanopoulos. An algorithm for real time control of critical intersections. Traffic Engineering and Control, **20**, 1979, 9–15.
16. Michalopoulos, P., G. Stephanopoulos. Oversaturated signal system with queue length constraints: single intersection. – Transportation Research, **11**, 1977a, 413–422.
17. Michalopoulos, P., G. Stephanopoulos. Oversaturated signal system with queue length constraints: sistems of intersections.– Transportation Research, **11**, 1977b, 423–428.
18. Mitani, M. Ohta. A practical evaluation method of Leq based on the beta distribution matched to the restricted fluctuation range in actual random noise.– Acoustica, **69**, 1989, 185–188.
19. Papageorgiou, M. Application of Automatic Control Concepts to Traffic Modelling and Control. Springer Verlag, Berlin, 1983.

20. Saenz, L., R. Stephens (eds.). Noise Pollution. John Wiley&Sons Ltd, 1989, p. 446.
21. Scemama, G. Traffic control practices in urban areas. Anual Review Report of the National Research Institute of Transport and Safety. Paris, France, 1990.
22. Shaw, E., N. Olson. Theory of Steady-state urban noise for an ideal homogenous city. – J. Acoust. Soc. Am. **51** (6), December, 1972, 1782–1793.
23. Singh, M., H. Tamura. Modeling and hierarchical optimization for oversaturated urban road traffic networks. – Int. Journ of Control, **20**, 1974, 913–934.
24. Singh, M., A. Titli. Systems: Decomposition, Optimization and Control, Oxford. UK, Pergamon press, 1987.
25. Strobel, H. Computer controlled urban transportation Systems. A survey of concepts, methods and experiences. – In: IFAC/IFIP/IFORS Conference on Control in Transportation Systems. Vienna, Austria, 1986, 25–45.
25. Taylor, I., C. Margaret, G. Geary. Queue volume – a measure of congestion. – Traffic Engin. Control, **28**, 1987, 582–585.
26. Yamaguchi, Sh., Y. Kato. A practical method of predicting noise produced by road traffic controlled by traffic signals. – J. Acoust. Soc. Am. 86 (6), December, 1989, 2206–2214.
27. Wan, C. L., K.W. Dickson. Road traffic monitoring using image processing – a survey of systems, techniques and applications. – In: IFAC Symposium: Control, Computers, Communications in Transportation, AFCET, Paris, France, 1989.
28. Zarkov, N., M. Konstantinova. Acoustic Characteristics of Sofia city (A. Marinov, ed.). Sofia, BAS, 1988 (in Bulgarian).

Эквивалентная уровень шума и оптимизация светофоров в трафике

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(Резюме)

Обсуждается проблема оптимального управления светофоров в трафике. В задаче динамической оптимизации уровень шума вводится как переменной состояния. Предложена замкнутая система управления, которая определяет продолжительность зеленого света в зависимости от эквивалентного уровня шума. Эта стратегия управления уменьшает шум в интенсивных пунктах движения. Показаны экспериментальные результаты.