Demand-Oriented Approach to Estimate the Operational Performance of Urban Networks With and Without Traffic Information Provision

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This paper addresses the problem of estimating the operational performance of extended urban transport networks under different conditions of traffic information availability. The suggested approach employs a simulation procedure for the real-time estimation of the network state, based on the dynamic assignment of an O-D matrix, which is adjusted by the prevailing traffic conditions. Next, a different procedure is used for the online simulation of the route diversion behavior of users under the influence of route guidance information. Moreover, the approach provides the prediction of the network state by hypothesizing about the adjustment of the travel behavior of users to the new traffic conditions generated by the routing information. The implementation of the approach on a part of a real urban network led to the determination of suitable information updating frequencies for providing the largest improvements in the various performance measures. The results signify the important role of taking into account dynamic changes in the O-D demand size for the plausible evaluation of the impact of information provision on the network performance for real-time traffic operations and transport planning purposes.

Keywords*:* Performance Measurement, Route Guidance Information, Traffic Assignment, Travel Demand, Urban Networks

1. Introduction

The development and implementation of models suitable for the real-time monitoring and control of extended traffic networks is particularly limited in the existing literature. In particular, current model implementations are mostly restricted to simplified linear (freeway) networks (Doan et al., 1999; Lindveld et al., 2000) or small-scale arterial street networks for local traffic control purposes (Tsekeris and Skabardonis, 2004). In addition, the dynamic traffic assignment (DTA) models currently used to describe (offline) the temporal evolution of network-wide traffic flows and travel times are fed with fixed (known) demand information (Ziliaskopoulos and Peeta, 2001). This information typically refers to historical or survey-based average estimates, which represent the customary travel pattern of users and reflects on a time-disaggregated (dynamic) target origin-destination (O-D) trip matrix. Existing approaches (see Polydoropoulou et al., 1994; Nihan et al., 1995) do not take into account the influence of mechanisms of users' cost adjustment to the new traffic conditions generated by the provision of route guidance (or routing) information or the action of other control measures, e.g. traffic signals, on the future traffic network performance. In this paper, the operational performance of a traffic network is described using several typical travel cost measures as well as a new one taking into account the changes in travel demand.

The methodological approach proposed here provides the simulated estimation of these performance measures in extended traffic networks without and under the effect of routing information. At the first stage, a combined dynamic O-D matrix estimation and DTA model is resolved for the real-time monitoring of the current (most recent) network traffic state using readily available link traffic counts. This stage provides the estimation of the network performance without the provision of traffic information. At the second stage, the most recent O-D matrix (estimated at the first stage) is loaded onto the network through another DTA model, which enables the online simulation of route diversion decisions of users under the effect of routing information. The latter model provides the calculation of the traffic network performance measures corresponding to the immediate future, i.e. over the next few seconds or minutes.

At the third stage, the proposed methodology provides the estimation of the future traffic network state by taking into account the impact of routing information on both the trip departure time and route choices of users. This impact includes changes in the size and the temporal distribution of the predicted O-D matrix. This final stage enables the prediction of changes in the most recent O-D matrix and, hence, the calculation of the network performance measures after the adjustment of the travel behavior of users to the traffic conditions generated under the effect of routing information. Section 2 presents analytically the models involved in each of the three steps of the suggested methodological approach. Section 3 describes the characteristics of the study area, that is the central part of the Greater Athens road network in Greece, in which the proposed approach is implemented. Section 4 and Section 5 investigate the network performance and the O-D demand profile respectively in both cases of the absence and presence of traffic information provision. Section 6 provides the estimation of a new, demand-dependent performance index, in comparison to an existing one. Section 7 includes the conclusions drawn from the present implementation of the suggested methodological approach.

2. Description of the stages of the proposed methodological approach

2.1 Estimation of network performance without traffic information provision

The first stage of the proposed approach provides the estimation of the most recent (current) network state, that is the spatio-temporal characteristics of the vehicular movements between each O-D pair, including the set of O-D path travel times, without the presence of route guidance information. The estimation of the most recent network state is based on the assignment onto the network of the existing travel demand pattern, as this is provided by the estimation of the most recent O-D trip matrix. The problem of the dynamic O-D matrix estimation is formulated as an entropy maximization model (Willumsen, 1984). This model is resolved through an algebraic reconstruction technique enhanced by a Newton-type diagonal gradient search, which has shown to be convergent under varied underlying assumptions concerning the demand structure and traffic counts, as described by Tsekeris and Stathopoulos (2003). The entropy maximization model can be expressed by the following objective function:

$$\max \; -\sum_{i \in N} \sum_{j \in N} x_{ij}^{\tau_d} \left[\log\left(\frac{x_{ij}^{\tau_d}}{\hat{x}_{ij}^{\tau_d}}\right) - 1 \right], \forall \;\; \tau_d \in \mathrm{T}_d \tag{1}$$

where $x_{ij}^{\tau_d}$ are the elements of the most recent O-D matrix, which denote the number of vehicular trips between the n^{th} O-D pair $(i-j)$, departing from origin $i \in N$ during departure time interval $\tau_d \in \mathrm{T}_d$ directed towards destination $j \in N$ and contributing to the flows traversing links $m \in M$ during count time interval $\tau \in \mathrm{T} \subseteq \mathrm{T}_d$, with $\tau \geq \tau_d$ and T_d the set of all departure time intervals. The study period T typically refers to the (morning or afternoon) peak traffic period. Correspondingly, $\hat{x}_{ij}^{\tau_d}$ denote the elements of the historical or target dynamic O-D matrix, which represents the customary travel pattern of users based on the output of a trip distribution model, the processing of partial traffic surveys and/or time-series of past dynamic O-D matrix estimates in the given study area. Possible sources of bias related to the estimation of the entropy model with objective function (1) (Van Zuylen, 1981) have been addressed here by the incorporation of appropriate normalization techniques (see Stathopoulos and Tsekeris, 2004), in order to improve the reliability of the target O-D matrix. The dynamic O-D matrix estimation model enables the adjustment of the target O-D matrix by the prevailing traffic conditions using time-series of traffic counts at selected network links across the given study period. These counts are automatically collected and processed in real-time to be fed to the O-D matrix estimation model. Let consider $M_O \subseteq M$ the total number of the observed links that contain a traffic counter, y_m^{τ} the observed traffic count on the m^{th} link during interval τ and $\hat{y}_m^{\tau}$ the assigned (estimated) volume on that link and count interval. The O-D matrix estimation problem is subject to the DTA constraints that ensure the consistency between the actual (counted) and the estimated (assigned) traffic flows. The basic relationship describing these constraints to the objective function (1) can be formulated as follows:

$$y_m^{\tau} = \sum_{i \in N} \sum_{j \in N} \alpha_{ijm}^{\tau_d \tau} x_{ij}^{\tau_d}, \; \forall \; m \in M_O, \;\; \forall \; \tau \in \mathrm{T} \tag{2}$$

The right hand side of equation (2) corresponds to the estimated link volume $\hat{y}_m^{\tau}$ on the m^{th} link during interval τ. The value of $\hat{y}_m^{\tau}$ depends on the elements $x_{ij}^{\tau_d}$ of the dynamic O-D matrix and the variables $\alpha_{ijm}^{\tau_d \tau}$. These variables are known as *link-use proportions* and they represent the elements of the assignment matrix A. Each of these elements determines the proportion of the trip demand $x_{ij}^{\tau_d}$ departing from some origin $i \in N$ during τ_d that contributes to the traffic flow y_m^{τ} on link $m \in M_O$ at interval τ.

These proportions are calculated here within a dynamic assignment model, as described in Stathopoulos et al. (1991), which it provides the simulation-based mapping of the O-D matrix to the link flows counted in each count interval. The model employs a deterministic macroscopic shortest path-finding procedure that is appropriate for real-time applications on extended traffic networks using commonly available PC facilities. This procedure is based on the *instantaneous* (or *reactive*) travel cost which users have experienced in the network (Ran and Boyce, 1996). Namely, each user departing from a particular location at any instant chooses the shortest path to his/her destination, based on the travel time perceived according to the currently prevailing traffic conditions. Thus, the procedure calculates at the beginning of each interval τ the time-dependent minimum-cost path from each origin i and, then, assigns each 'packet' of simulated vehicles departing from the corresponding origin i onto the 'best' route in order to reach the intended destination j. More detailed information on the formulation and solution of the model is provided in (Tsekeris and Stathopoulos, 2003). The cost calculation functions used in the model take explicitly into account the effect of congestion, queues and oversaturation (at those junctions where traffic demand exceeds capacity) on the network performance, in terms of the link travel times, as described in (Van Vliet, 1982).

The present modeling formulation can be extended to represent reducing levels of ability of users to change (adjust) their trip departure time under the prevailing traffic conditions. This can be carried out by placing lower and upper bound constraints within the estimation procedure in order to intrinsically control the deviations of the adjusted trip departures from those trip departures assumed by the target O-D matrix. Examples of such optimization algorithms that could provide maximum-entropy O-D matrix estimates from traffic counts with bound constraints include those proposed in (Byrne, 1998). Nonetheless, such a formulation would reduce the ability of the combined dynamic O-D matrix estimation and DTA model to reproduce the actual traffic conditions, and would result in smaller improvements in the operational performance of the network, in the case of hypothesizing users' adjustment to traffic information (see 2.3).

The accuracy of representing the prevailing traffic conditions based on the assignment of the most recent O-D matrix onto the network is evaluated here within the statistical criterion of *GEH*, as proposed by the U.K. Highways Agency (1996). The magnitude of *GEH* indicates whether the differences between the measured y_m^{τ} and the estimated link flows $\hat{y}_m^{\tau}$ are statistically significant or non-significant. The value of *GEH*, which is averaged over all observed links $m \in M_O$ for each count interval $\tau \in \mathrm{T}$, is given as follows:

$$GEH = \sqrt{\frac{(y_m^{\tau} - \hat{y}_m^{\tau})^2}{(y_m^{\tau} + \hat{y}_m^{\tau})/2}} \tag{3}$$

Based on equation (3), in the case where the average value of *GEH* is lower than 5 (*GEH* < 5) for at least the 85% of observed links $m \in M_O$, then it can be considered that the estimated flows $\hat{y}_m^{\tau}$ do sufficiently replicate the actual (measured) traffic conditions, without statistically significant differences. The *GEH* criterion provides a state-of-practice measure for the evaluation of errors in assigned flows, based on the typical assumption of Poisson distribution. This assumption is generally adapted for such purposes, provided that the determination of the type of variation of flows, particularly in real-time network applications, is practically impossible. Moreover, the use of nonparametric statistical measures, such as *GEH*, carries minimal requirements about assumptions pertaining to the population characteristics (Pagano, 1994) and, hence, it is suitable for evaluation tests, as the present one.

2.2 Estimation of network performance with real-time traffic information provision

The second stage of the methodology refers to the estimation of the network performance under the effect of real-time traffic information provision to the users. The simulated path-changing behavior of users during their trip implementation is investigated by assuming a number of different frequencies in which the traffic information is updated. These information updating frequencies are defined by *control intervals* π, which may be equal to or, typically, shorter than count interval τ. The estimation of the operational performance of the traffic network is carried out through the use of another dynamic traffic assignment procedure, referred to as Dynamic Network Assignment (DNA). The structure of the DNA model, which is analytically described in another study (Tsekeris and Stathopoulos, 2005), is based on a rolling–horizon estimation and implementation framework. In this framework, the route choice behavior of users is constantly updated using the assumption that users receive, accept and are able to follow the route guidance information provided to them within each control interval π, in which the count intervals $\tau \in \mathrm{T}$ are subdivided, until the end of study period T.

The DNA model uses the same shortest path-finding procedure and cost calculation functions as the dynamic assignment procedure used at the first stage (see 2.1). However, the DNA procedure assumes that users take (update) their path decisions on the basis of the *actual* travel cost during their trip implementation in the network. Namely, the simulated route choice decisions do not remain the same after the instant that users depart from their initial origin (source) but they are updated at the beginning of each control interval π (e.g., of one-min length) based on the traffic conditions prevailing in the network at the previous control interval π-1.

The en-route changes in the traffic demand conditions are simulated by the DNA procedure through the loading onto the network of a *combined* demand matrix during each control interval π. This combined matrix constitutes the sum of three different demand matrices. The first one refers to the *queue matrix*, which captures the suppressed traffic demand of the queuing vehicles at the oversaturated junctions at the end of each interval π. The second one refers to the *transient demand matrix*, composed of the number of uncompleted trips that are stored at the end of each control interval π to the furthest reached *transient* zone or junction along the currently estimated shortest path. The third one corresponds to that demand matrix which is obtained from the disaggregation (time partitioning) of the most recent O-D matrix to a number of sub-matrices equal to the number of control intervals.

Thus, the sequence of the simulated route choice decisions assumed to have been taken by the users at the beginning of each control interval π within study period T can finally result in the use of O-D travel paths that differ considerably from those paths initially selected from them at the instant of their departure from the source. The extent of the rerouting or diversion of users from these initially selected shortest paths depends on the varying levels of traffic congestion in the network, as well as the frequency of updating information during their trip implementation. Namely, growing levels of congestion will be expected to favor the route-switching response of users, particularly under high information updating frequencies (such as that of 30 sec), and lead to larger changes in the network performance (Tsekeris and Stathopoulos, 2005).

2.3 Prediction of network performance by hypothesizing users' adjustment to traffic information

The third stage of the proposed methodology is based on the prediction of a dynamic O-D matrix that represents the travel demand under the hypothesis about the adjustment of the trip departure and route choice behavior of users to the new network traffic conditions generated by the provision of routing information. The predicted O-D matrix is calculated using the same procedure to that used for estimating the most recent O-D matrix (see 2.1), but on the basis of the information obtained from the simulated link flows, as produced by the DNA model. More specifically, the link traffic volumes, $\hat{y}_m^{\pi}$, that are estimated by the DNA model during each control interval π are aggregated over intervals of duration equal to the duration of the count interval τ (e.g. of 15-min length).

In turn, the aggregated volumes $\sum_{\pi \in \tau} \hat{y}_m^{\pi}$ for each observed link $m \in M_O$ are used as the new 'actual' traffic count information for the dynamic prediction of the new O-D matrix, in combination with the dynamic traffic assignment procedure based on the instantaneous traffic cost definition, as described in 2.1. In this case, the instantaneous travel cost represents the new travel cost experienced by users after their hypothesized adjustment to the traffic conditions under the influence of traffic information provision. The predicted O-D matrix is loaded onto the network using the DNA model in order to calculate the new values of the various performance measures under the effect of routing information and the hypothesis about the adjustment of the trip departure time and route choice behavior of users. The accuracy of representing the simulated 'actual' traffic conditions based on the assignment of the predicted O-D matrix onto the network is evaluated using the *GEH* statistics for each count interval $\tau \in \mathrm{T}$, as described in 2.1.

Moreover, the reliability of the (most recent) estimated O-D matrix (2.1) and the predicted O-D matrix is examined using the Student *t*-test statistics. This reliability analysis provides a measure of the statistical significance of the changes in the structure of the estimated and predicted O-D matrices with respect to structure of the target O-D matrix, due to the effect of traffic information provision. A suitable measure for calculating the reliability of the estimated and predicted O-D matrices is the Confidence Interval (*CI*) of the Change Error in the Structure (*CES*) of the O-D matrix, which is given as follows:

$$CI = \sum_{\tau \in \mathrm{T}} \frac{(CES)_{\tau}}{n} \mp t_{95} \left[\frac{\sigma}{\sqrt{n}} \right], \tag{4}$$

where $$(CES)_\tau = \frac{1}{Z}\sum_{i\in N}\sum_{j\in N}\frac{\left|x_{ij}^{\tau_d} - \hat{x}_{ij}^{\tau_d}\right|}{\hat{x}_{ij}^{\tau_d}}$$

and $$\sigma = \sqrt{\frac{n\sum_{\tau\in T}(CES)_\tau^2 - [\sum_{\tau\in T}(CES)_\tau]^2}{n(n-1)}}$$

Where n is the total number of count intervals $\tau \in T$ and Z is the number of O-D pairs with trip flows during study period T. Equation (4) provides the Lower Confidence Interval (*LCI*) and the Upper Confidence Interval (*UCI*), according to the negative or positive sign respectively, of the *CES* of the estimated or predicted O-D matrix, in comparison to the structure of the target O-D matrix. The value of t_{95} determines the *LCI* and the *UCI*, according to the confidence level of 95% of the Student *t*-test statistics.

The reliability measure (4) expresses the extent of possible changes in the customary O-D travel pattern of users, as it reflects the target O-D matrix, due to the provision of traffic information. Provided that users are assumed to reach their final destination (sink) at the end of study period T, measure (4) is a proxy for calculating the effect of changes in departure time within period T, due to the adjustment of their simulated behavior by the prevailing traffic conditions (in the first stage) and the new traffic conditions generated by the routing information (in the third stage). The estimated (at the first stage) and the predicted (at the third stage) O-D matrices, based on the objective function (1), show the (most favorable) maximum-entropy trip departure pattern, while seeking to reproduce actual and simulated traffic conditions, as described in Section 3. In turn, the route guidance strategy, implemented through the DNA model, employs the adjusted trip departures in minimizing path travel times of users in the network.

3. Characteristics of the present application of the methodology

The proposed estimation methodology is implemented in the inner road network of Athens, Greece, which is illustrated in Figure 1, composed of 44 (departure / arrival) zones. The target O-D matrix corresponds to the morning period T (from 6:00 am to 9:00 am) of a Monday in February 2000. This matrix has been estimated using a combination of travel survey estimates and historical dynamic O-D matrices based on link traffic counts collected across the timescale 1989–2000 (Stathopoulos and Tsekeris, 2004). The traffic counts, which correspond approximately to the 10% of the total network links, are fed to the combined dynamic O-D matrix estimation and DTA model every 15 minutes, which is the duration of the count interval τ.

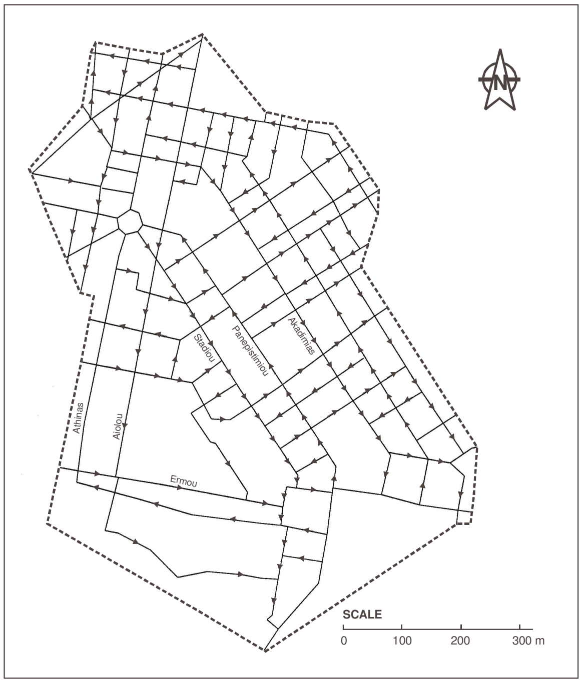

Figure 1. Graphical representation of the inner road network of Athens used in the study

The effect of the frequency, in which the routing information is updated, is investigated by assuming control intervals of different duration, such as those of 900 sec, 300 sec, 60 sec and 30 sec. The results of the *GEH* error statistics indicate that the estimated (at the first stage) and the predicted (at the third stage) traffic flows reproduce without statistically significant differences the actual and the simulated (produced by the DNA model) traffic flows respectively (Figure 2). More specifically, in all cases considered, the assignment of the estimated O-D matrix and, particularly, of the predicted O-D matrices onto the network produces link traffic flows at observed links with $GEH < 5$ at a percentage equal or higher than 85% over the whole study period T. The fact that the above acceptance criterion is satisfied for each specific count interval τ only in the case of using shorter control intervals π ($\leq$ 300 sec) signifies that such intervals can lead to a more accurate prediction of the network traffic conditions, in comparison to longer control intervals, such as that of 900 sec.

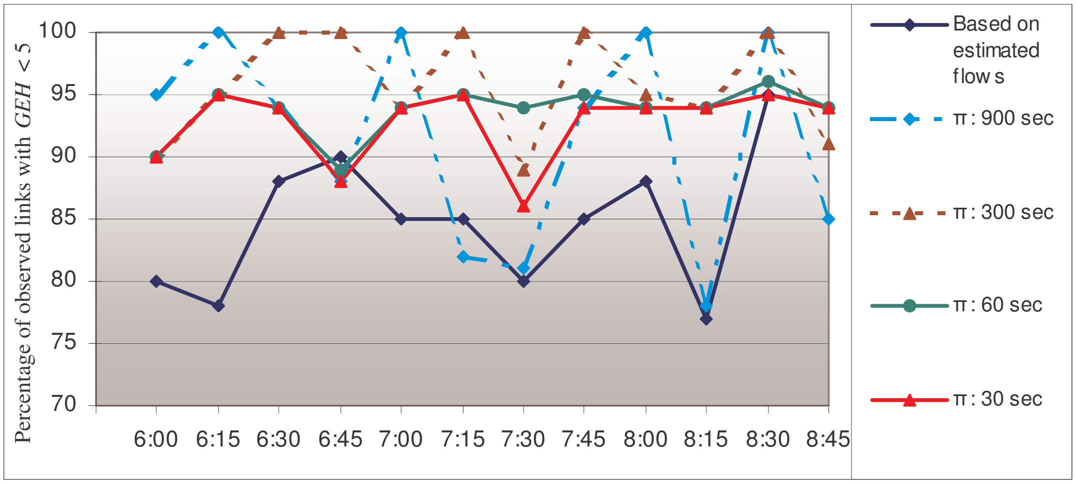

Figure 2. Results of GEH error statistics for different information updating frequencies and loading conditions

4. Impact of providing routing information on the network performance

The operational performance of the traffic network is estimated here using three different measures, in addition to two performance indices analyzed in Section 6. These measures refer to the *V*ehicle-*H*ours *T*raveled (*VHT*) in veh-hrs/hr, the *V*ehicle-*K*ilometers *T*raveled (*VKT*) in veh-km/hr and the *A*verage *T*ravel *S*peed (*ATS*) in km/hr. Figures 2, 3 and 4 illustrate respectively the changes in the magnitude of *VHT*, *VKT* and *ATS* with respect to different durations of control interval π. These changes are investigated with regard to three different loading cases. In the first case, the performance measures are obtained from the loading of the target O-D matrix onto the network through the DNA model. In the second case, the performance measures are obtained from the loading of the most recent O-D matrix (estimated at the first stage) onto the network through the DNA model. In the third case, the performance measures are obtained from the loading of the 'predicted' dynamic O-D matrix (estimated at the third stage) onto the network through the DNA model.

By the consideration of these cases, the proposed approach can provide useful insight into the effect of different travel choices of users, such as departure time choice and route choice, on the operational performance of the network, under both the assumptions of absence and presence of traffic information provision. More specifically, in the absence of traffic information provision, the loading of the target O-D matrix onto the network through the DNA model shows the impact on network performance of changes in route choice only, in comparison to the loading of the most recent O-D matrix, where the impact of changes in departure time choice is also taken into account. Under the presence of traffic information provision, the loading of the 'predicted' O-D matrix onto the network through the DNA model allows for the impact of changes in departure time choice on network performance to be assessed, in comparison to simulating the diversion responses of users in real-time, where only changes in route choice behavior are considered.

The results demonstrate that the loading of the most recent O-D matrix leads to the significant reduction of the *VHT* for the longest control intervals (of 900 sec and 300 sec) and the increase of the *ATS* for all control intervals, in comparison to the loading of the target O-D matrix. However, the loading of the most recent (estimated) O-D matrix results in the increase of the *VKT*, particularly for the shortest control intervals (of 30 sec and 60 sec), in comparison to the loading of the target O-D matrix. This behavior may be attributed to the *path spreading* effects of the routing information provision. Namely, this information makes some users to avoid the mostly used paths which include links with high levels of traffic congestion and to follow longer O-D routes so that diminish the travel time spent in the network.

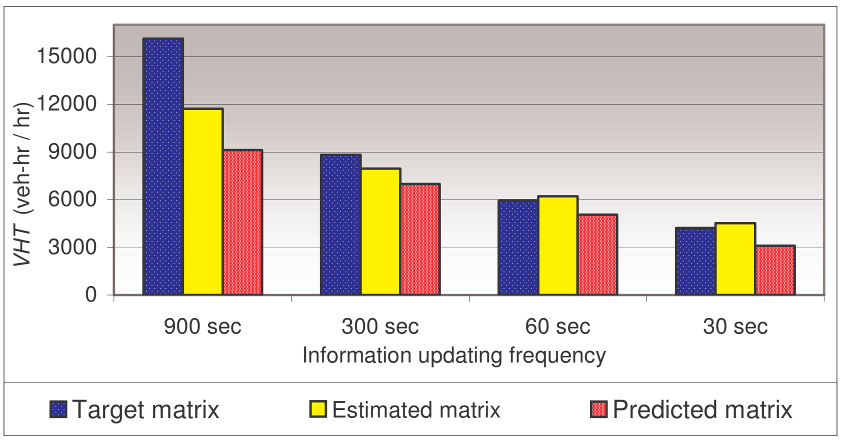

Figure 3. Changes in the VHT (veh-hrs/hr) for different information updating frequencies and loading conditions

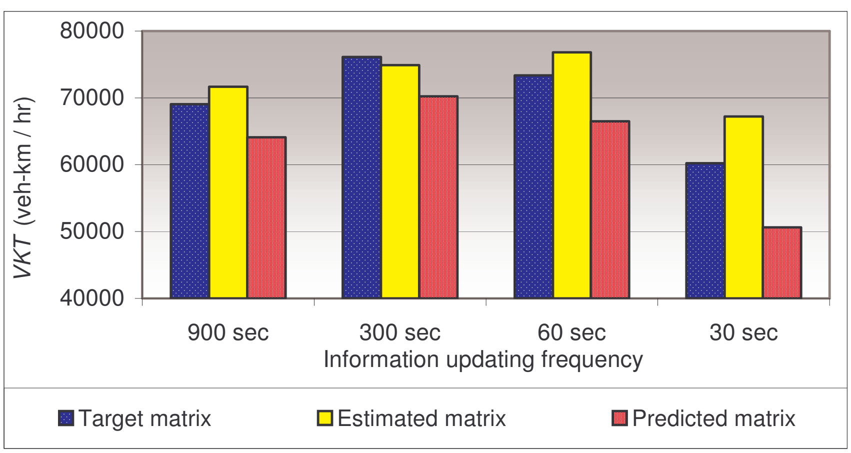

Figure 4. Changes in the VKT (veh-km/hr) for different information updating frequencies and loading conditions

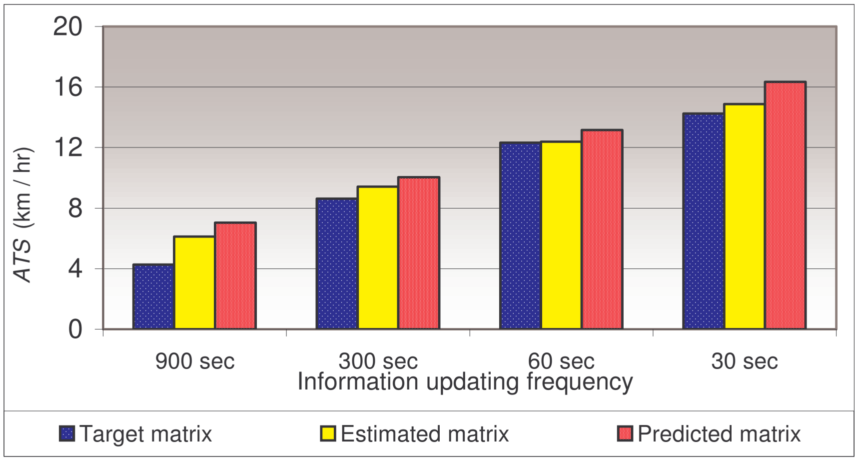

Figure 5. Changes in the ATS (km/hr) for different information updating frequencies and loading conditions

On the other hand, the loading of the predicted dynamic O-D matrix leads to significantly smaller travel times (Figure 3) and larger average travel speed (Figure 5), particularly for reducing duration of control interval π, in comparison to the case of using the target O-D matrix as well as the estimated dynamic O-D matrix. In addition, the future traffic network performance is considerably improved in terms of the reduction of the total distance traveled by users (Figure 4), especially for short control intervals, such as that of 30 sec. These results demonstrate that the hypothesized adjustment of the trip departure time and route choice behavior of users to the new traffic conditions under the effect of routing information cause a considerable reduction of the network congestion levels. In turn, the less travel times and the higher travel speeds enable users to decrease the traveled distances to the desired destinations by avoiding detouring and path spreading in the network.

5. Impact of providing routing information on the O-D demand

5.1 Changes in the size and temporal distribution of O-D demand

Figure 6 illustrates the temporal evolution of the trip demand across the given study period on the basis of the target O-D matrix, the estimated dynamic O-D matrix and the predicted dynamic O-D matrices that correspond to the control intervals of 900 sec, 300 sec, 60 sec and 30 sec. The loading of the predicted dynamic O-D matrix leads to significant changes in the size and temporal distribution of O-D demand, in comparison to the case of using the target O-D matrix and the estimated dynamic O-D matrix. In particular, the adoption of shorter control intervals (30 sec and 60 sec) results in the increase of the predicted demand size through the release of trips comprising *latent demand*, in comparison to the demand size corresponding to the target O-D matrix and, especially, to the estimated dynamic O-D matrix. This demand growth may be considered as the result of the reducing travel times and the increasing travel speeds in the links of the central part of the network due to the routing information provided to users within the above control intervals.

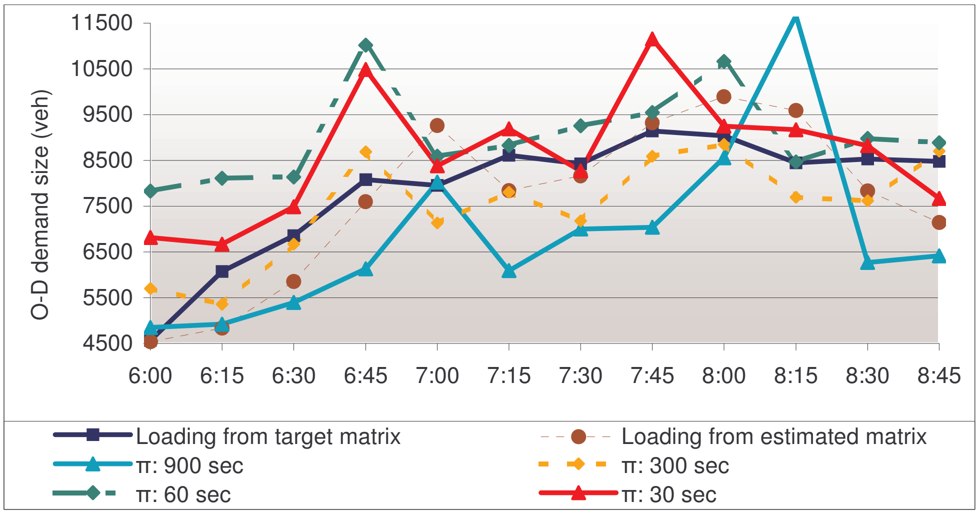

Figure 6. Changes in the O-D demand size over time for different information updating frequencies and loading conditions

On the contrary, the usage of longer control intervals (300 sec and 900 sec) leads to the decrease of the predicted demand which can be satisfied within the study period, in comparison to the demand size corresponding to the target O-D matrix and to the estimated O-D matrix. This decrease can be attributed to the fact that the improvement of network congestion conditions due to traffic information provision within such long control intervals is not so significant as to give rise to growth of latent demand, as it was observed in the case of using shorter control intervals (30 sec and 60 sec). Consequently, some users, after the hypothesized adjustment of their travel decisions to the new traffic conditions under the influence of information, probably prefer to shift their trip departure time before or after the study period or select travel paths that include links outside the given study area.

5.2 Statistical analysis of changes in O-D demand

Table 1 shows that the *CES* of the predicted O-D matrices is significantly increased (except of the case of using a control interval of 300 sec), based on the Student *t*-test statistics (see 2.3), in comparison to the *CES* of the estimated O-D matrix. This increase receives its highest value for the shortest control interval of 30 sec. In other words, the provision of traffic information affects considerably the simulated O-D travel choices of users, in comparison to the case of no information provision, particularly when this information is provided within such high updating frequencies as that of 30 sec. In addition, table 1 presents the Confidence Interval Length (*CIL*), as defined by the difference $CIL = UCI - LCI$, for different information updating frequencies and loading conditions. The magnitude of the *CIL* for the prediction of the O-D matrices corresponding to the shortest control intervals, i.e. those of 60 sec and 30 sec, demonstrates a significant increase, in comparison to the *CIL* for the prediction of the O-D matrices corresponding to the longest control intervals, i.e. those of 300 sec and 900 sec as well as to the *CIL* for the estimated O-D matrix.

Table 1. Estimated values of *CES*, *LCI*, *UCI* and *CIL*

Statistical measure	Based on estimated matrix	900 sec	300 sec	60 sec	30 sec
CES	1,93	2,11	1,64	2,08	2,24
LCI	1,69	1,76	1,31	1,67	1,81
UCI	2,06	2,46	1,98	2,48	2,67
CIL	0,37	0,70	0,67	0,81	0,86

These results show that the reduced duration of the interval in which the routing information is provided to users increases the statistical significance of the temporal dispersion of the predicted O-D matrix cells, in comparison to the target O-D matrix. The greater dispersion of the predicted O-D trips may justify the fact of the reduction of the network congestion levels in conjunction with the increase of the demand size serviced when using the shortest control intervals (of 30 sec and 60 sec). Moreover, the results signify that the adoption of shorter control intervals increases the need for collecting new demand information about the adjusted travel behavior of users in order to make the target O-D matrix more realistic and enhance the reliability of the predicted O-D matrices.

6. Estimation of performance indices

As it was described in previous sections, the proposed methodology enables the estimation of the network performance in relation to changes in the size and temporal distribution of O-D demand. The effect of these changes on the network performance can be also manifested through the calculation of two different performance indices. Performance indices (*PI*) typically provide a measure of the *productivity* of the network within a given period of time, using a combination of different attributes of operational performance, such as the *VHT* and the *VKT*. The first performance index, referred to here as *PI1*, is expressed by the following ratio (Chen et al., 2001):

$$PI1 = \frac{VKT}{VHT} \tag{5}$$

The above index, *PI1*, essentially provides the vehicle-km-weighted speed (in km/hr) in the network over the set of time intervals in which the study period is subdivided. However, the ability of the *PI1* to represent actual changes in the productivity, in terms of the throughput of the network is limited. This is due to the fact that rerouting of users, after providing them with traffic information, can lead to longer but faster routes and, hence, to an increase of the magnitude of *PI1* without any real benefit for the network productivity.

In addition, a new performance measure is proposed here, referred to as *PI2*, which enables the calculation of the operational performance of the network in relation to changes in the size of O-D demand, as this is dynamically estimated (see 2.1) across the successive intervals of the study period. More specifically, *PI2* is given by the following ratio:

$$PI2 = \frac{Total\ O-D\ Trips}{VHT} \tag{6}$$

The measure of *PI2* (in veh/veh-hrs/hr) expresses the proportion of the total amount of O-D trips serviced during period T over the total travel time spent per hour that is required to satisfy the demand for these trips. Figure 7 demonstrates the different behavior of the two performance indices, *PI1* and *PI2*, under the influence of traffic information provided over increasing updating frequencies, ranging from 900 sec to 30 sec.

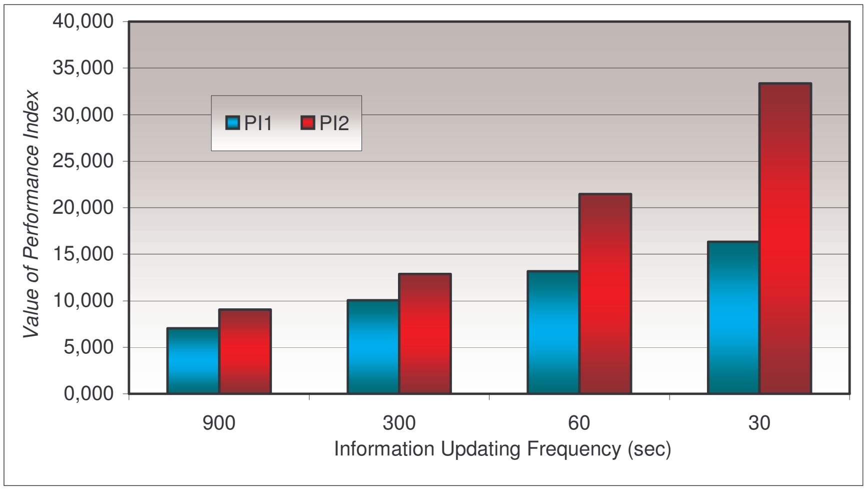

Figure 7. The behavior of performance indices PI1 and PI2 under the influence of traffic information provided over different updating frequencies

The numerical value of *PI2* is rapidly increasing when the duration of control interval becomes smaller than 60 sec, in comparison to the relatively smoother rate of increase of *PI1* value over the whole range of updating frequencies. This difference can be attributed to the growth of the size of latent demand, which is taken into account by index *PI2*, for these shortest updating frequencies, in conjunction with the corresponding reduction of travel times. Thus, the adoption of the demand-sensitive index *PI2* leads to an increase of the predicted magnitude of productivity in the network under the effect of traffic information, in comparison to the magnitude of productivity predicted on the basis of index *PI1*.

7. Conclusions

The present paper described a demand-oriented methodological approach for estimating the operational performance of extended traffic networks, particularly under the effect of routing information provision. This information is based on the real-time estimation of the most recent O-D trip matrix using time-series of actual traffic counts. The estimation of the most recent O-D matrix provides a better representation of the prevailing traffic conditions, in comparison to those produced by the loading of the historical target O-D matrix onto the network. The loading of the most recent O-D matrix onto the network using the DNA model enables the online monitoring of users' responses to the provision of route guidance information. The results of the present application, which refers to a realistic road traffic network, demonstrated the significant impact of traffic information provision on the network performance, in terms of the reduction of travel times and the increase of travel speeds, due to changes in the trip departure time and route choices of users.

Moreover, the suggested approach provides the predicted O-D matrix and, hence, the operational performance of the network at its future state, by hypothesizing about the adjustments in the trip departure time and route choices of users to the new traffic conditions under the effect of routing information. It was found that these adjustments lead to significant further improvements in the aforementioned measures of network performance, as well as to the increase of the predicted O-D demand size (latent demand), while reducing the total distances traveled in the network. The introduction of new, demand-sensitive performance measures, such as the one proposed here, which it takes into account changes in the size of O-D demand, can provide a more plausible evaluation of the beneficial effect of routing information on the operational performance of extended traffic networks.

The proposed methodology can be used to enhance the design and evaluation of the operation of Advanced Traveler Information Systems (ATIS), particularly in terms of selecting suitable information updating frequencies. The application of appropriate validation procedures concerning the modeling of the route diversion behavior and the effect of the rate of penetration and rate of acceptance of users to the provided traffic information is expected to advance the usage of the proposed methodology for the real-time deployment of ATIS. Such validation procedures are currently developed using probe vehicles and implementation of experimental subscriber-based information systems such as cell phone traffic alerts.

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