MAPPING TRAFFIC MANAGEMENT SYSTEMS DATA INTO DETAILED NAVIGATION NETWORKS.

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ABSTRACT

This paper addresses the problem to represent the information of a high level strategy into navigation network (NN), via mapping on it Traffic Management Systems data from a strategy network (SN). In this way the navigation system of the driver or the central navigation system can take into consideration historical traffic conditions, traffic events that comes from the high level network and other relevant data useful for navigation purpose. The proposed methodology applies a User Equilibrium approach to transfer information from SN to NN assuming that the demand in NN is represented by the arc flows estimated in SN.

KEYWORDS
Road Network Representation, Traffic Observation, Traffic Management, Traffic Assignment, Personal Navigation, Route Guidance.

INTRODUCTION

High level networks in the context of Traffic Management Systems (TMS) are defined with the aim to represent traffic in wide urban or interurban road systems with specific mathematical models that are manageable to implement control strategies. After an action has been decided by the strategy, during the operational phase it shall be provided to the single driver/vehicle. This need is particularly relevant for V2I (Vehicle to Infrastructure) applications that are currently under study and implementation (CVIS project, [5]). Since applications and services should operate in an open framework for TMS, to assure interoperability among ITS, the need to use their traffic management measures (e.g. travel time, flow, density) and primarily their strategy actions is becoming relevant also for navigation network to activate advanced services (e.g. Dynamic Route Guidance). In a static route guidance system, vehicles have devices on board for helping users in choosing the best path in the road network, where users have to communicate their position (even with an automatic location system) and the desired destination of their trip, then the system provides the route. In a Dynamic Route Guidance (DRG) system, if the current traffic state information is available, the recommended paths are defined on the basis of actual or predicted traffic conditions and the recommendations can be frequently updated. Simple strategies in the selection of information, which suggest individual shortest paths, could generate adverse impact on traffic flows, if the share of devices among drivers is high. For this reason, to avoid concentration phenomena [1], [3] it is necessary to take into account the global effect of information on the network, by solving a route guidance problem.

In this paper we address the problem to represent the information of high level strategy (strategy network -SN) into navigation network (NN), via mapping TMS network data from a strategy network (SN). In this way the navigation system of the driver or the central navigation system can take into consideration historical traffic conditions, traffic events that come from the high level network and all the relevant traffic data useful for navigation purpose. An option to match data of the two representation levels of road network is to assume the same topological structure for both networks and differentiate the level of detail only for data associated to links. This is the approach adopted, for example, in an integrated environment for micro and macro traffic simulation [2] to manage different models based on the same data base structure. If we observe the attributes of a link, some of them represent data for micro-simulation, and others, as the volume-delay function, are used for the user equilibrium assignment at macro level. Nevertheless, for large networks a detailed representation with a great number of links can increase difficulties in network modeling calibration phase. Therefore for TMS purpose a simplified network topology is usually built by selecting relevant road elements and grouping small segments.

To focus on a real life application, in order to provide *route guidance* to the driver into the urban road network, two user information systems - one individual and one collective - have been adopted within the area of 5T project (Telematic Technologies for Traffic and Transport in Turin). Both systems have been modeled on a high level network, where control operates with two techniques: prediction (or feed-forward) to anticipate a possible approximate equilibrium state and feed-back, to keep the state close to the equilibrium [6]. In the 80’s there was some trial on mapping back information from high level network (SN) to navigation network (NN). The proposed method foreseen to define a linear mapping between the SN and NN, and use the inversion of the mapping to provide the information from SN to NN. Since physicality of the information was lost, the method was then extended by projecting to minimum norm the information defined in SN to NN and considering the arc characteristic as the link capacity, which provided better performance. To better describe the case, consider multiple arcs of NN mapped to a single arc of SN. By projecting back the quantity, e.g. flow, taking into consideration the capacity of the original link will assign larger flow to larger capacity link and less to reduced capacity link. This consideration shall then be maintained with the interpretation of sub-set of a partition of the set of the paths defined in the NN, when projecting back the information to the original network NN. Simple back-mapping or proportional back-mapping usually do not proper work since will exhibit favorable traffic condition on minor arteries, thus diverging real traffic there.

PROBLEM STATEMENT

The high level network, called strategy network (SN) uses a graph built of oriented arcs or edges (*e*) that connect nodes (*n*). The graph also contains particular nodes describing the origins and the destinations of journeys called centroids (*c*). The Navigation Network (NN) is composed of junctions (*j*) and links (*l*), which have a geometrical representation (e.g. polyline, see fig. 1). We define *I(e)* the initial node of the arc *e* and *F(e)* the final node. Let define M : NN->SN the mapping of NN links to SN arcs.

We define the Strategy Network on a directed connected graph, whose edges are subset of the possible partition of the paths defined on the Navigation Network. This definition implies that each edge of the SN is built by a set of distinct paths in NN. Of course, not all partition has traffic meaning, while is it possible that some arcs on the NN are included in paths that define distinct arcs of SN. Some arc and path defined in NN may not be represented in any arc of SN. For example this happens with arcs that are outside the study area of the SN. From a practical point of view a path in NN can represent a road and in another case there can be separate paths for the main and the secondary road. These elements may not have relevance in the SN network, while they have for navigation proposes.

A high level approach is based on arc-node network representation, where nodes model the major intersections and arcs describe the road infrastructures that connect them. In a detailed level, the description of the networks requires a detailed modelling of all the road sections where vehicles can travel, the intersections and the roundabouts, by an explicit description of vehicle maneuvers. Road sections at SN levels are therefore represented in terms of oriented arcs, whose features are defined in terms of numerical attributes, i.e. capacity, number of lanes, a proper volume-delay function, also called cost function. The level of detail of the SN depends on the specific scope of the TMS: in some cases, there is a selection process of roads to be represented, in other ones, all of the roads have to be modeled in SN, also as aggregate links. On the contrary, at NN level the road network representation contains a high number of data since all segments are described. A useful reference for NN description is the level 0 of GDF –ISO standard [7]. GDF also consider a level 2 for describing high-level features of the network, which could be used to represent a SN modeling. At SN level, nodes representing intersections may include a definition of the set of the allowed turning maneuvers, which are described using turning rules between input and output arcs. When considering the crossing cost of a node, a specific function or rule shall be defined which associates to the attributes of input and output arcs and their flow, the cost of crossing in term of delay. There are some property of the SN, the NN and their relationship, in particular:

1) card(NN)>=Card(SN), i.e. each arc of SN represents one or more link of the NN. It is in general possible that an entire set of paths of the NN, i.e. a sequence of links, is represented by an arc of the SN, i.e. the mapping M is onto;

2) it is possible that does not exist *l*(NN) -> *e*(SN), i.e. some links of the NN are not represented by the SN (Fig. 1);

3) the SN is in general limited in space and level of representation, i.e. the SN covers only a limited area covered by the NN.

Assuming that consistency between the two networks is appropriately solved from the topological point of view (because the connectivity of the nodes between SN and NN is maintained by the mapping M), remains what is the most critical consistency problem: how to translated information contained into the SN level in NN and reciprocally. One of the current problems is that the data do not have a common storage, since a SN usually derives from a TMS, managed by a local authority in a specific area, while a NN is provided on board the vehicles and it is defined by map providers. This situation requires building the mapping between the SN and NN using automatic or manual operations. An interface between the two information levels requires that both network representations at SN and NN levels respectively are consistent, also in terms of link and turning information. The Origin-Destination matrix used in SN (by means of its centroids) have not a correspondence in NN, since the information exchanged between the two networks (flow, density, travel time) is only related to arcs-links and turnings elements.

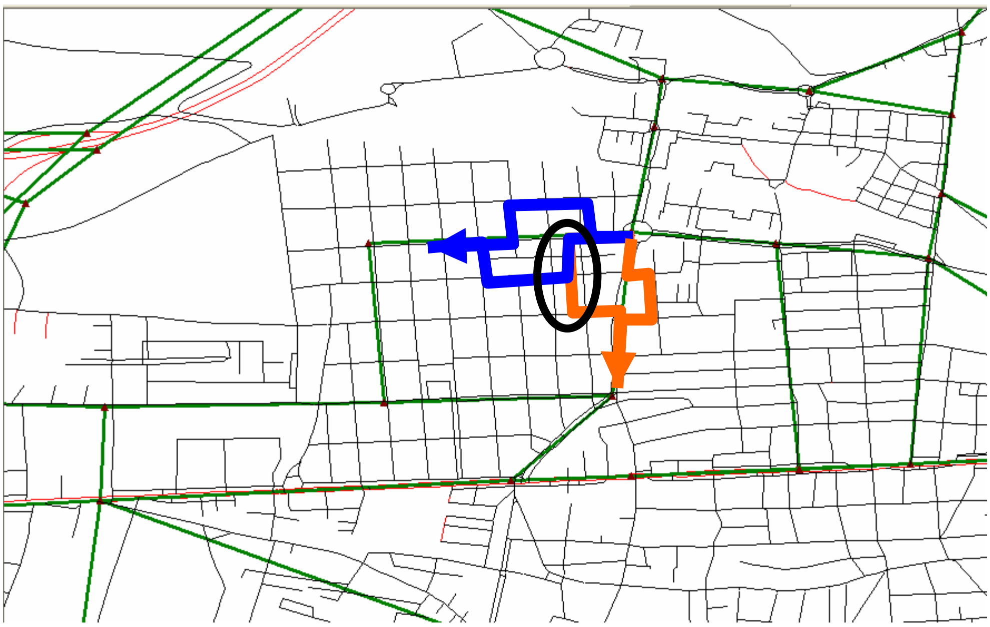

Figure 1 - Example of the paths in NN (in black) related to arcs in SN ((in green)

The problem addressed in this study is to map a quantity (q), as a measure of a control strategy, i.e. travel time or traffic flow, from the SN to NN, i.e. $q_{SN}(e)$->$q_{NN}(l)$. This problem generates the following main points that need to be solved:

1) in general case information on a link *l* of NN can derive by one or more arcs of SN, since it can be included in more than one path in NN, that *e* of SN represents (Figure 1);

2) the mapping shall take into consideration that some links of NN are not "fully" represented by the SN, or are completely excluded in the SN model. It can generate an undesired problem, as to estimate travel time unexpected low, thus potentially diverging a relevant part of the traffic flow in these roads.

SOLUTION PROPOSED

As described before, by considering that a single arc of the SN can represent a set of paths of the NN, the idea is to create a relationship between paths in NN and arcs in SN. Note that in our proposal, to detect links in NN where transfer information coming by SN, only the paths in NN connecting nodes of the same arc in SN are considered. In other words, we see SN as a realization of a subset of a partition of the paths defined in NN. A quantity of an arc in SN is then mapped back to the elements of the set formed by those paths in NN, which the arc *e* represents.

Let consider the following problem: having defined the quantities in SN, back mapping this information to the NN network. Since associated to an arc of SN can be multiple path in NN and the path can refers to the same arcs of another arc of SN, a proper mapping to the quantities define on SN shall be define. For example, if q1 and q2 are the quantities on 2 arcs *e1* and *e2* in SN to be back-mapped to NN, it shall be defined an operation to define the quantity on any arc *l* in NN, i.e.

$$q(l) = f(q1(e1), q2(e2)),$$

where f = {sum, max, min,…}, *l* in NN and the quantities *q1(e1), q2(e2)* are defined in the SN, i.e. *e1,e2* in SN and the function can be defined depending on the quantity under study. In the following section this function is defined implicitly using a traffic network loading procedure of SN quantities (in this case the traffic demand is expressed by SN arc flows) into NN where nodes in SN are assumed as centroids on NN and their arc flow the traffic demand flow.

Assumptions and general notes

If we consider that any node in SN can be related to one or more nodes in NN for complex intersections (see the network modeling in level 2 of GDF and the table which contains the list of segments that forms the intersection). The first case (Figure 2, on the left) can be managed by means of an automatic procedure in most cases, for example, when coordinates of the nodes of the two levels have similar values. The second case (Figure 2, on the right) usually needs a manual association of nodes in database.

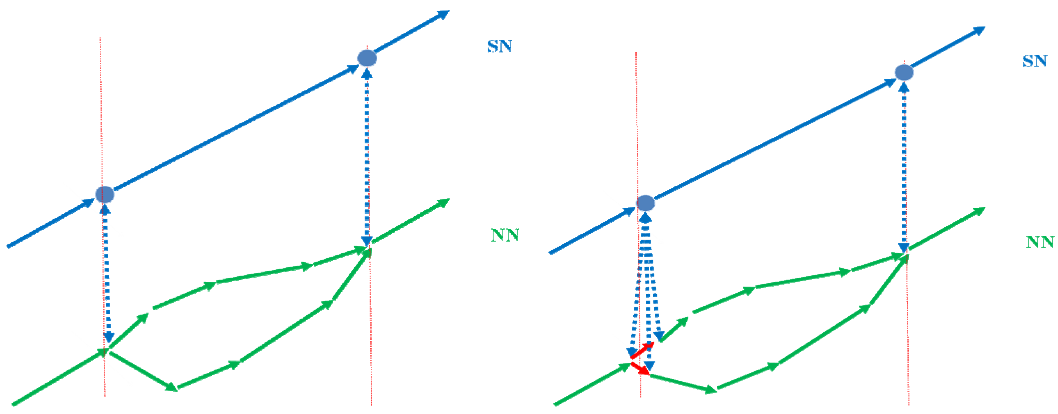

Figure 2 - Case of correspondence between nodes in SN and NN (left hand) and connection with dummy links for node in SN and NN (right hand)

In this last case, a table to connect each node in SN to links in NN is required; it contains dummy links that assure the connection between the two networks also according to the information on turning restrictions. For those nodes in NN which are not related to SN nodes (Figure 2), input and output traffic flows defined on SN arcs has been considered not relevant by TMS. For example there are links where travel times do not change over time and its relevance is low, so TMS does not collect data to model them in a detailed form. In the mapping procedure between SN and NN four main cases can be recognized:

- *segmentation*, when an arc in SN represents a sequence of links in NN;
- *split*, when an arc in SN represents multiple parallel links or paths in NN (Figure 2);
- *mixed*, when more links on SN model the same link in NN (Figure 4);
- *external*, when in SN only selected paths of NN are modeled.

In order to avoid that route choice suggestions could concentrate traffic flows on minor links of the NN where data are not available from TMS, the following method has been proposed to exchange traffic information between the two networks. A cost function for any link of NN is needed and it can be built by using available information on NN database. Usually NN tables provide length, speed, type of road and the number of lanes for all links; although in an approximate way, this information allows us to define a simplified cost functions for all the links in NN. Minor links should be set with a low value of capacity to avoid an excessive traffic loading.

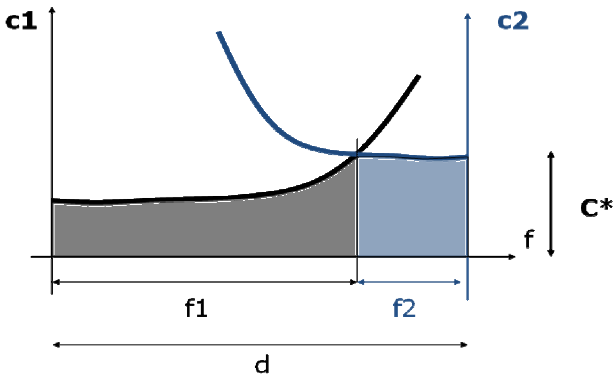

Figure 3 – User Equilibrium (UE) solution for a 2 links network

Using the link cost function is possible to find a solution for link flow and cost (or travel time) that distributes the traffic flow on alternative paths, if we consider that all paths connecting the same pair of nodes of an arc in SN have the same travel time. As known, this solution represents a User Equilibrium flow network configuration, UE [4]. In Figure 3 a solution of this problem is represented for a two link network with two cost functions *c1=f(f1)* and *c2=f(f2)*, where *c** is the equilibrium cost when the demand *d* is divided in *f1* and *f2*.

The method

During a time period *T*, *f*or each arc *e* in SN, connecting node $I_{SN}(e)$ to node $F_{SN}(e)$, an estimation of the arc flow *f(SN)* is given by TMS which operates on SN. Since nodes I_{SN} and F_{SN} are connected to the NN network by means of one or more dummy links, it is possible to consider these nodes as centroids for the NN. Therefore the arc flow f(SN) can be assumed as an OD flow in the NN, where an assignment procedure can be applied (Figure 5).

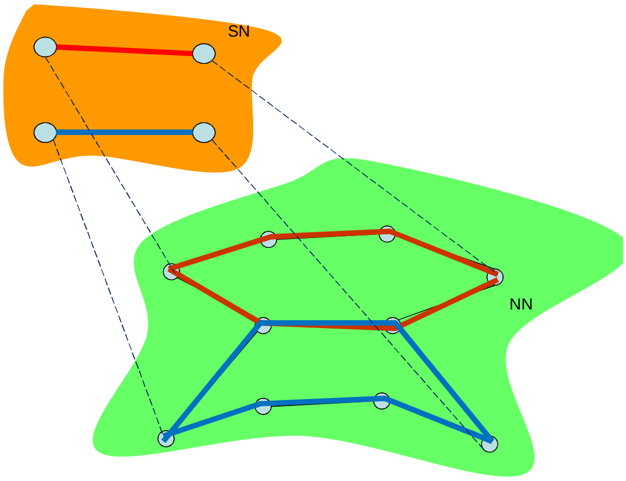

Figure 4 - Path flow overlapping on a link in NN

The part of the NN involved in the UE solution can be limited to a sub-network between the two nodes, therefore the closer part to I_{SN} and F_{SN} or, in a general case, to the entire network NN which details the SN under consideration. In the first case, the set of paths for each couple of nodes needs to be defined (e.g. in a link-path incidence matrix **A**). In a general case, it is useful not to exclude a priori links of NN which are not mapped on SN, since otherwise their estimated travel time could not be updated with the SN traffic information. Note that enlarging the part of the NN where the assignment is applied assures a better estimation of overlapping phenomena (Figure 4) between flows on the NN links deriving from the flows of different arcs in SN. However, the UE solution assures that all of the paths between the same I_{SN} and F_{SN} pair have the same cost value and a flow that takes into account the capability of the roads to "receive" or "manage" traffic, depending on their cost function form. For the assumed flow configuration in NN, the sum of all the path flows between 2 nodes of SN is equal to the flow on SN that connects the two nodes. In the simple case where only one path in NN is available, then the assignment of the arc flow in SN is entirely done to that path of NN. A validation of the travel time estimation can also be performed on the consistency of data, since from SN we know also the arc costs (travel time). Indeed these values can be compared with the costs estimated on the paths in NN, using the same cost functions adopted to compute the UE solution. The travel time calibration procedure to align data between SN and NN can differ for the following cases (see Figure 5):

- when a sub network is not mapped into the SN (partial information on traffic flow is available from SN) the flow correction is implemented;
- when the alternative paths in NN are modelled in SN (the model is quite sure on traffic flow data) the cost function should be calibrated.

Equipped vehicles (Floating Car Data) can also contribute to calibrate and validate the SN definition (that can requires a SN update), the NN cost functions and the mapping rules. An adequate setting of the cost function parameters can allow also to apply a selection of those links on the NN where flow should be avoided (e. g. assuming for local roads a strong link capacity constraint on traffic flow).

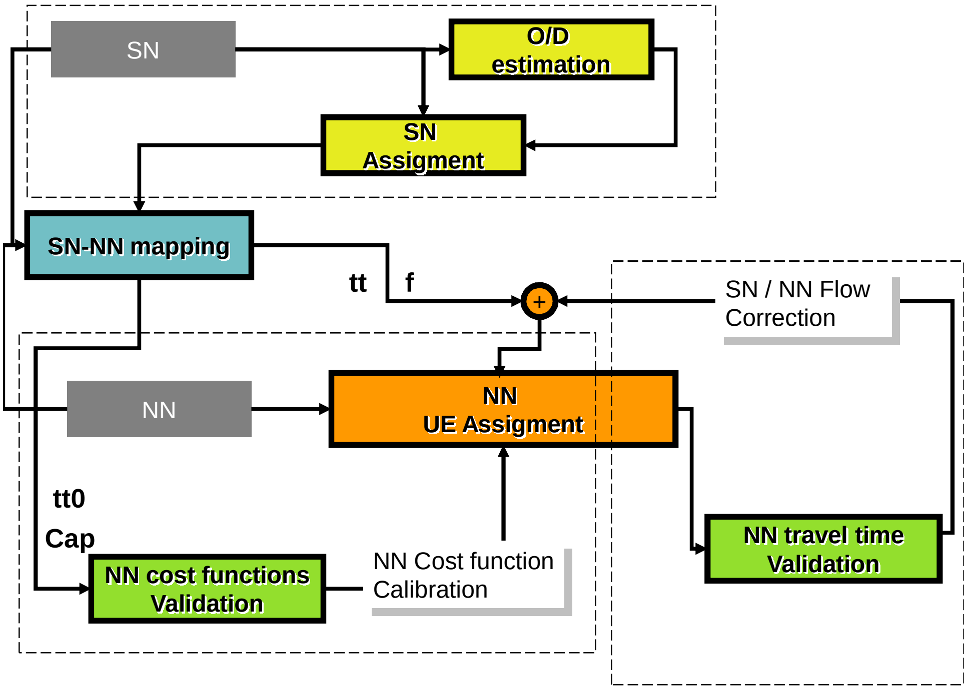

Figure 5 - Relationships between mapping and validation procedures on NN

EXPERIMENTAL ANALISYS

The environment adopted

An ideal context to test the mapping procedure presented here is an individual route guidance service, where the number of vehicles equipped with devices is negligible or when the rate of overlapping between paths is low. In these cases, an expected result of the mapping of SN information on NN is a time saving, for trips from Origin to Destination, with regards to the case of absence of SN information for NN (a new better route is available). A second result is the presence of new options for drivers in the network, when more than one path is available at the same traffic conditions. The general requirements of the scenarios analyzed are the following:

- simple test network (Figure 6) which reproduces a portion of a urban congested road network (speed range on links is between 10 and 40 km/h);
- SN is an external reference network which gives as output travel time and flow on its arcs for Deterministic User Equilibrium (DUE) solutions;
- for NN, BPR link cost functions are used to simulate traffic congestion (*tt(l)=tt0(l)*[1+a (f(l)/Cap(l))^b]*); free flow time (tt0) and capacity (Cap) have been set according to SN data; a =3, b=4);
- the demand involves 4 OD pairs (2 main flows, 1 secondary flow and a local flow- see Table 1);
- at least 2 alternative paths for any OD pair are available on SN and therefore on NN;

- a difference between travel time in free-flow conditions for three alternative paths is observed in the same network (low, medium and high differences).

Tests have been carried out in Matlab®. The SN and NN Traffic Assignment procedures have been implemented adopting a Frank-Wolfe algorithm, as described in [4].

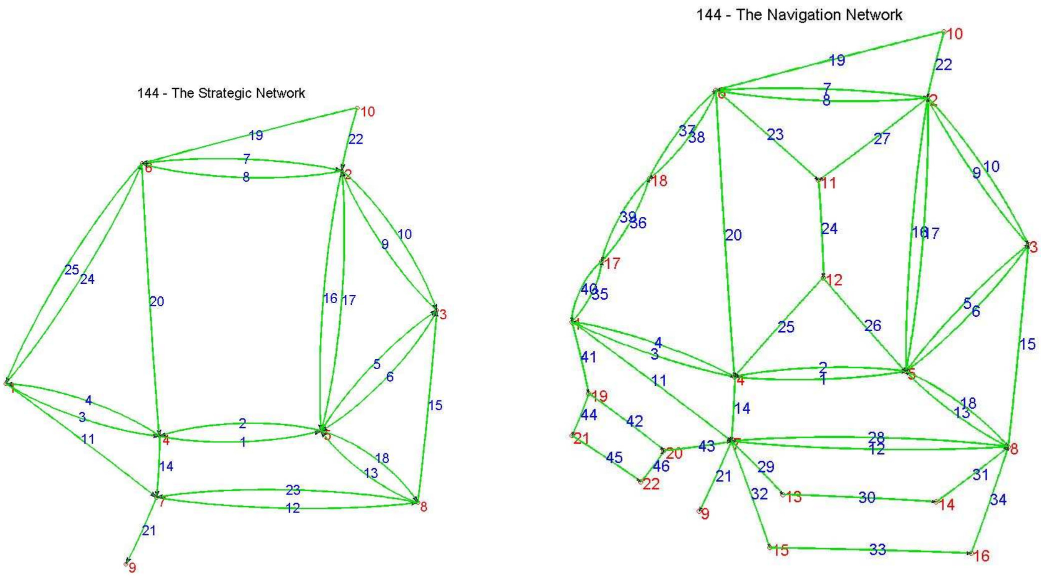

Figure 6 – Graphs of SN and NN for the test network

The test cases

Based on the general conditions described before, several sub-cases were generated (Table 1) for simulating variations of traffic conditions on the network, caused by increases of demand levels and known in SN (uniform and not uniform among OD pairs).

Table 1 – Features of test cases

Test code	*Demand level*	*OD (1,3)*	*OD (2,8)*	*OD (10,9)*	*Local OD (1,8)*	*Expected results*
297	0	100	100	10	0	Only one path is advantageous from 1 to 3 for SN and NN
144	1	3000	1000	10	0	At least 2 paths are advantageous from 1 to 3 in SN and in NN
445	2	6000	1000	10	0	At least 1 new path in NN becomes advantageous from 1 to 3 (it is modeled as aggregated in an arc of SN – *split* case)
900	3	6000	1000	10	300	Also a new path in NN, which is not represented in SN, becomes advantageous from 1 to 3 (*external* case)
688	4	6000	1000	2000	0	Also a new path in NN, which is shared on 2 arcs in SN, becomes advantageous from 10 to 9 (*mixed* case)

The first results

In the following, the first results of our experiments are reported with regards to the aims to explore. Indeed, by changing the demand from level 0 to 1, the OD flow 10 to 9 is moved to a new path for SN and NN, therefore if another faster route (travel time saving) is available, the congested one is avoided.

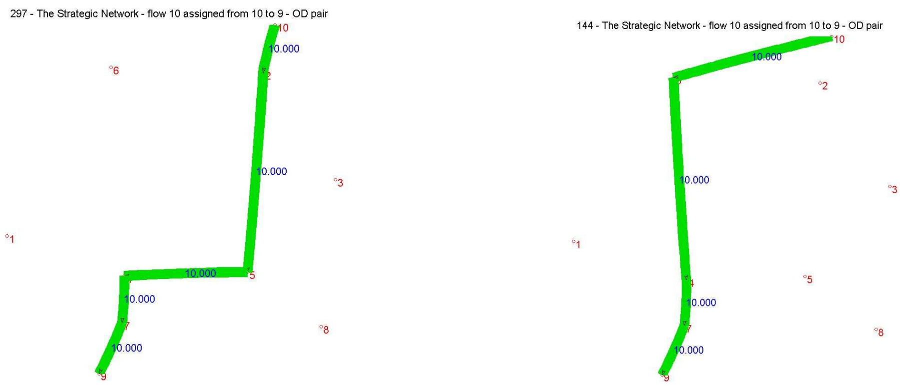

Figure 7 – Path changing from 10 to 9 (level 0 to 1)

The gradual activation of alternative paths in NN (DUE solution) can be observed comparing the results with demand level 0, 1 (Figure 8) and 2 (Figure 9), where NN links, modelled as aggregate in an arc of SN (*split* case – on the left hand in Figure 9) are involved in advantageous paths (crossing the links (13,14) and (15,16)). Comparing level 2 and 3, we observe that NN links not represented in SN are activated as effect of the local OD flow (*external* case - for paths crossing the link (19,20) and marked in red in Figure 9). In Figure 8 and Figure 9 the activation of new paths in equilibrium solution evidences that their travel time is comparable with other alternative paths.

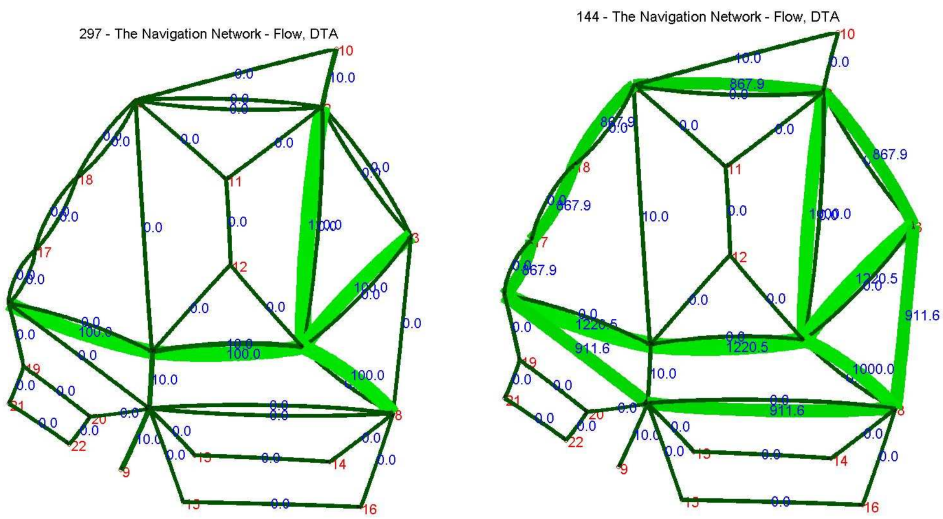

Figure 8 - Equilibrium paths on NN for level 0 and 1

The requirement regarding the protection of local streets, with their exclusion from advantageous paths when the demand is not too high, is also satisfied, since only NN links represented in SN are activated until level 1 (Figure 8), on the base of travel time savings criterion. Finally we observe an appropriate estimation of travel time also for links in NN shared among more arcs of SN, because in level 4 a new path becomes advantageous (crossing link (11,12)).

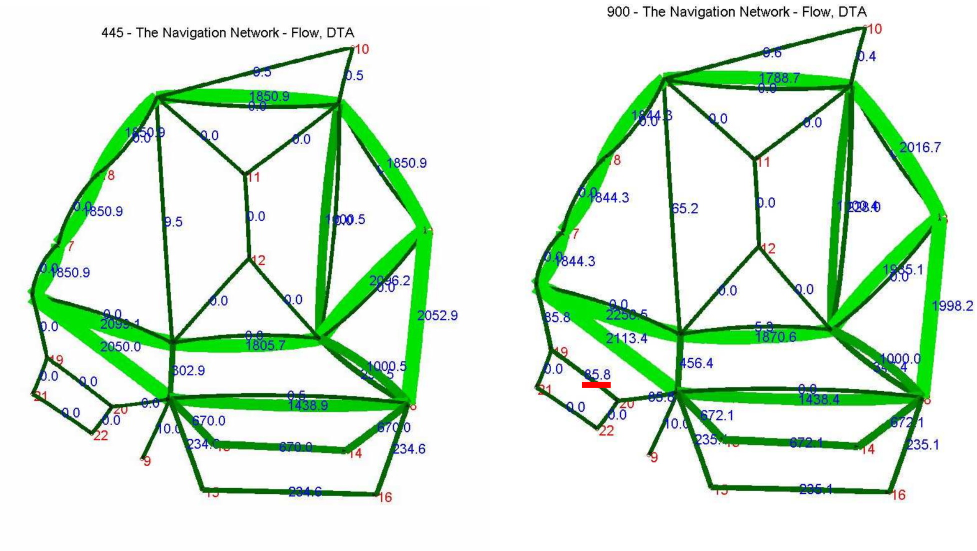

Figure 9 - Equilibrium paths on NN for level 2 and 3

CONCLUSIONS

This paper proposes a method to transfer traffic information between two network models describing the same road network with two different levels of details. A high level approach is based on arc-node network representation, called Strategy Network (SN), where nodes describe intersections and arcs the road infrastructure. In a detailed level, the network description requires a detailed modelling of the road sections, intersections, and roundabouts with a representation of vehicle maneuvers, i.e. Navigation Network (NN). The level of detail of the SN depends on the specific scope of the TMS: in some cases, there is a selection process of links to be represented, in other ones, all of the roads have to be modeled in SN.

By considering that a single arc of the SN represents a set of paths of the NN, the idea is to create a relationship between paths in NN and arcs in SN. In other words, we see SN as a realization of a subset of a partition of the paths defined in NN. The relationship between SN and NN is defined using a traffic assignment procedure of SN quantities (i.e. traffic demand expressed by SN arc flows) into NN where nodes in SN are considered centroids on NN.

The contribution of this paper to the literature is the proposal of a methodology which is able to consider, for route guidance purpose, relevant information available for TMS on its own network, which usual manages traffic information with a low level of detail. The results, at this stage of the research, show that the proposed model solves relevant points, taken into account as requirements for our problem. Indeed, the experimental analysis shows that, when the demand level increases, a gradual activation of new advantageous paths is observed in the test network, on the base of travel time saving criterion in a User Equilibrium network configuration. On the other side, tests performed reveal that minor streets are almost excluded from available paths for navigation until a local traffic demand is simulated.

Further research activities need to be carried out to implement on real road networks the assumptions and the models here defined, in order to test with real data if the improvement on the quality of data for navigation purposes gives the expected results.

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