INDY : A New Analytical Multiclass Dynamic Traffic Assignment Model[1]

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1 Introduction

In order to analyze transportation networks for planning purposes, traffic assignment models have shown to be a useful tool, reason why these models have been applied for many years now. Although static models are still widely used, the theory and practice of dynamic models have evolved significantly over the last 10 years. This resulted in a shift of focus from static traffic assignment to dynamic traffic assignment (DTA) in both research and (commercial) applications. In this paper, a new analytical multiclass DTA model, called INDY, will be presented. In the next section, a brief overview of different approaches to DTA will be given. Section 3 then describes the proposed model. An application to a large-scale network, the Dutch national network, will be presented in Section 4. Conclusions and further research are mentioned in the last section.

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2 Approaches to dynamic traffic assignment

A DTA model typically describes route choice and the way in which traffic dynamically propagates through a network. A nice overview of DTA models is given in Peeta and Ziliaskopoulos (2001). Two main approaches can be distinguished: (1) *analytical models* that express the route choice and traffic propagation by a set of mathematical equations on a macroscopic level, and (2) *simulation-based models* that describe the processes by a set of rules on a mesoscopic or microscopic level.

Analytical DTA models (e.g. Ran and Boyce, 1996, Bliemer and Bovy, 2003) are defined as a mathematical programming problem, an optimal control problem, a complementarity problem, a (quasi) variational inequality problem, or a fixed-point problem. The advantage of these models is that solution properties can be examined and that convergent algorithms for solving the problems exist from the literature. Another advantage is that solving the problem does essentially not become more time consuming and does not require more computer memory when travel demand increases, since they are formulated on a macroscopic level. This means that they are suitable for large area networks. However, most analytical models proposed in the literature fail in solving DTA problems on large networks because of their computational complexity, such that they are only applicable to small to medium-sized networks. This includes models using a dynamic network load (DNL) procedure as proposed in e.g. Astarita (1996) and Xu et al. (1999). Also, the inclusion of multiclass traffic with different route choice behaviors *and* different flow propagation for each user-class is not a straightforward extension of these models.

On the other hand, simulation-based models (see e.g. Ben-Akiva et al., 1994, and Mahmassani et al., 1993) have shown to be able to deal with realistic large-scale networks. Furthermore, they offer a more flexible environment for including more detail and realism in the flow propagation (such as queuing and traffic control). Including multiclass traffic is, especially in models based on microsimulation, relatively easy. However, as mentioned in Li (2000), since these models are heuristic, convergence cannot be guaranteed and it is very hard to obtain any insight into the DTA problem from them. Additionally, the computation time and memory requirements of simulation models are proportional to the level of travel demand, therefore simulation models may not be feasible for networks that cover a large area with many trips.

In this paper we propose an analytical DTA model based on a DNL procedure that incorporates different user-classes in a very general way and is capable of solving problems on large-scale networks, thereby overcoming two major shortcomings of current analytical models, while keeping the advantages of analytical models.

3 Description of INDY

INDY (INteractive Dynamic assignment model) is a route-based analytical multiclass DTA model. INDY has been implemented as an operational dynamic link library (DLL) for a Windows PC that can be used within different graphical user-interfaces and applications. INDY is implemented in a smart way to reduce computer resources without affecting the DTA outcomes, thereby enabling the applicability to large networks. The general framework of the model is depicted in Figure 1. The model basically consists of a route generation component for making the route choice sets for each OD pair with nonzero demand, an analytical dynamic network loading (DNL) component and a route choice component. These components will be described in more detail below. First it is explained what kind of user-classes typically can be distinguished in the model.

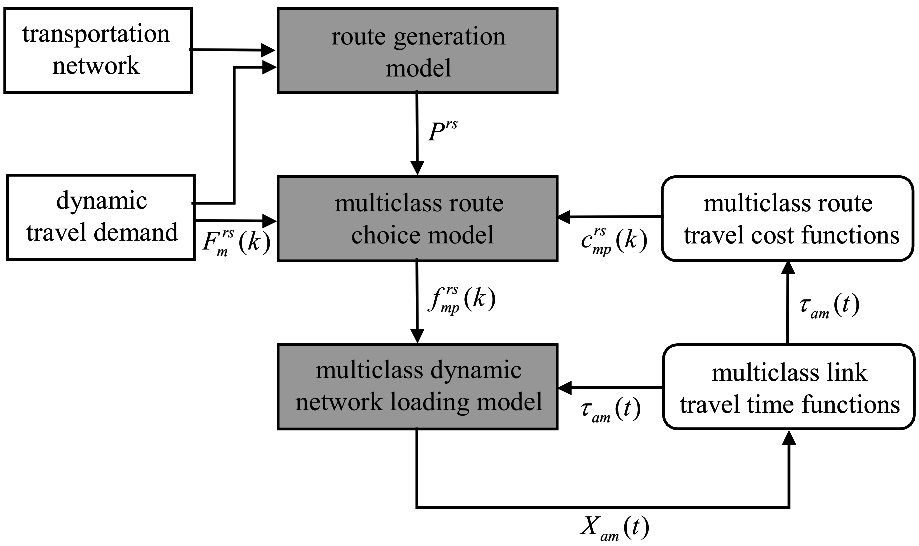

Figure 1: Framework of INDY

3.1 User-class definitions

User-classes can be defined as specific vehicle types or driver types with different characteristics and preferences. They can be distinguished by e.g. speed limit, driving style, vehicle size, road segments that are accessible, route choice preferences and parameters, etc. A typical example would be considering passenger cars and trucks. A truck usually drives slower than a car, occupies more space, may face dedicated infrastructure (truck lane), and probably has a higher value of time. In the model, user-classes appear in the route component as well as in the DNL component.

In the route choice component, each user-class may have a different route travel cost function. Unlike other analytical DTA models, user-classes may also have entirely different link travel time functions (depending on the flows of all user-classes) for propagating traffic through the network. Proposed multiclass DTA models to date and even some simulation-based DTA models consider the same link travel time for all user-classes or let them only vary by an affine relationship (e.g. Ran and Boyce, 1996, and Mahmassani et al., 1993), which clearly does not hold during congestion.

3.2 Route generation component

INDY applies exogenous route generation before executing the DTA model instead of route searching during the model runs. The route generation is run only once. The main advantage is that it saves a large amount of computing time during the model runs, since the route choice alternatives are readily available and no expensive dynamic shortest path computations are necessary during a model run. By using a pre-determined set of routes, also non-additive cost components (e.g. route tolls) can be modeled easily and a greater freedom exists in applying route choice models (e.g. in dealing with route overlap). A disadvantage of route generation in advance is that one cannot be sure that all paths that would be used in a traffic equilibrium are included in the route set. However, by choosing appropriate values for the parameters in the route generation procedure, a representative set of sufficiently distinct routes can be obtained. It is also possible to check for missing routes after a model run by performing an additional shortest path computation based on the model outcomes.

In INDY, two approaches for route generation have been implemented: (1) a Monte Carlo approach as proposed in Catalano and Van der Zijpp (2001), and (2) performing a static traffic assignment. Both approaches are very fast procedures and provide similar and reasonable route sets. The second approach has the benefit that it also provides initial route choice proportions for faster convergence of INDY. The obtained route set P^{rs} will be input for the route choice model where each of the route alternatives will be considered and route flows will be assigned.

3.3 Multiclass route choice component

For each OD pair (r,s) and each user-class m, the traveler has the choice to take any of the available alternative routes in set $P_m^{rs} \subseteq P^{rs}$ and will choose the best route available (depending on the information available, i.e. perfect or imperfect information on traffic conditions) based on the actually experienced travel cost (which need not consist of travel time only) or take a fixed route as a habitual driver. The route choice model is formulated as a variational inequality problem using a dynamic extension of Wardrop's equilibrium conditions and is iteratively solved using the method of successive averages (MSA) on the route flows. In each iteration, an analytical DNL problem needs to be solved, which propagates the route flows $f_{mp}^{rs}(k)$ on route p departing origin r at time k through the network and which gives rise to adapted travel times and travel costs. This DNL component is discussed in the next paragraph.

3.4 Multiclass dynamic network loading component

The heart of INDY is the analytical multiclass DNL model, which 'simulates' traffic propagating over routes over time. Its inputs are the route flow rates $f_{mp}^{rs}(k)$ while the output will consist of time-dependent link flow rates, link densities, and link travel times for each user-class. The DNL model can be written as a system of equations as an extension of the single class system of Chabini (2001). The equations consist of flow conservation constraints, flow propagation constraints, definitional constraints and the link travel time functions. The flow conservation constraints can be written as

$$u_{amp}^{rs}(t) = \begin{cases} f_{mp}^{rs}(t), & \text{if link } a \text{ is the first link on path } p \in P_m^{rs}, \\ v_{a'mp}^{rs}(t), & \text{if link } a \text{ is after } a' \text{ on route } p, \end{cases} \tag{1}$$

where $u_{amp}^{rs}(t)$ and $v_{amp}^{rs}(t)$ respectively are the link a inflow rate and outflow rate at time instant t of user-class m following path p from r to s. For each vehicle type, the flow propagation constraints describe how the vehicles move along their routes over time:

$$V_{amp}^{rs}(t) = \int_{w \in W} u_{amp}^{rs}(w)dw, \text{ with } W = \{w \mid w + \tau_{am}(w) \le t\}, \tag{2}$$

where $V_{amp}^{rs}(t)$ is the cumulative outflow corresponding to the dynamic class- and path-specific outflow rates $v_{amp}^{rs}(t)$, and $\tau_{am}(t)$ is the link a travel time for user-class m when entering the link at time instant t. Equation (2) basically states that the cumulative link outflow at time instant t is given by all inflows that have entered the link and also exited the link at time instant t. This equation also holds if FIFO is not satisfied, although we would like to have FIFO satisfied within a user-class (not across user-classes). The following definitional constraints are included:

$$v_{amp}^{rs}(t) = \frac{dV_{amp}^{rs}(t)}{dt}. \tag{3}$$

$$U_{amp}^{rs}(t) = \int_{w=0}^{t} u_{amp}^{rs}(w)dw. \tag{4}$$

$$X_{am}(t) = \sum_{(r,s)} \sum_{p \in P_m^{rs}} X_{amp}^{rs}(t), \text{ where } X_{amp}^{rs}(t) = U_{amp}^{rs}(t) - V_{amp}^{rs}(t). \tag{5}$$

$U_{amp}^{rs}(t)$ is the cumulative inflow corresponding to the dynamic class- and path-specific inflow rates $u_{amp}^{rs}(t)$, and $X_{am}(t)$ is the number of class *m* users on link *a* at time instant *t*, which is by definition the difference between the cumulative inflow and the cumulative outflow at time instant *t*. The class-specific link travel time functions may depend on all user-classes present on the link at the time of entrance, i.e.

$$\tau_{am}(t) = D_{am}[X_{a1}(t), \ldots, X_{am}(t), \ldots, X_{aM}(t)], \tag{6}$$

where $D_{am}(\cdot)$ is a nondecreasing function from $\mathbb{R}^M$ to $\mathbb{R}$, where *M* is the number of user-classes. Note that these multiclass link travel time functions are very general and can even include more variables. Clearly, in order to get realistic results these functions need to satisfy some properties. For example, the link travel times for all user-classes should converge during congestion. Fore more information on multiclass travel time functions, see Bliemer (2001).

A time-discretized version of this system of equations can be solved by adapting proposed algorithms from the literature. We adapted an algorithm from Chabini (2001) such that it can take the user-class interactions and their impact on the traffic operations into account.

4 Case study: Dutch national road network

To show the validity of INDY and the capability of dealing with large networks, we present a numerical example of a dynamic assignment on the Dutch national road network. Figure 2 shows the network, which consists of all freeways in The Netherlands and other main arterials and urban roads. For completeness in analyzing effects on the Dutch network, it also includes part of the main networks of Germany and Belgium.

The network consists of 25,434 directed links (with given capacity, speed limit, and road type), 10,801 nodes, and 400 zones. The travel demand consists of a 24-hour dynamic trip matrix with two user-classes, passenger cars (class 1) and trucks (class 2). The total number of vehicle trips is 7.3 million (6% by trucks). The Monte Carlo route generation model produced 181,567 routes in just 5 minutes for the 109,292 OD pairs with nonnegative travel demand, which is on average 1.66 route per OD pair. This may seem little, but taking into account that the network is mostly a freeway system with many triangular shapes, there are many OD pairs for which only one route is actually a realistic option. The maximum number of routes generated for an OD pair is 14.

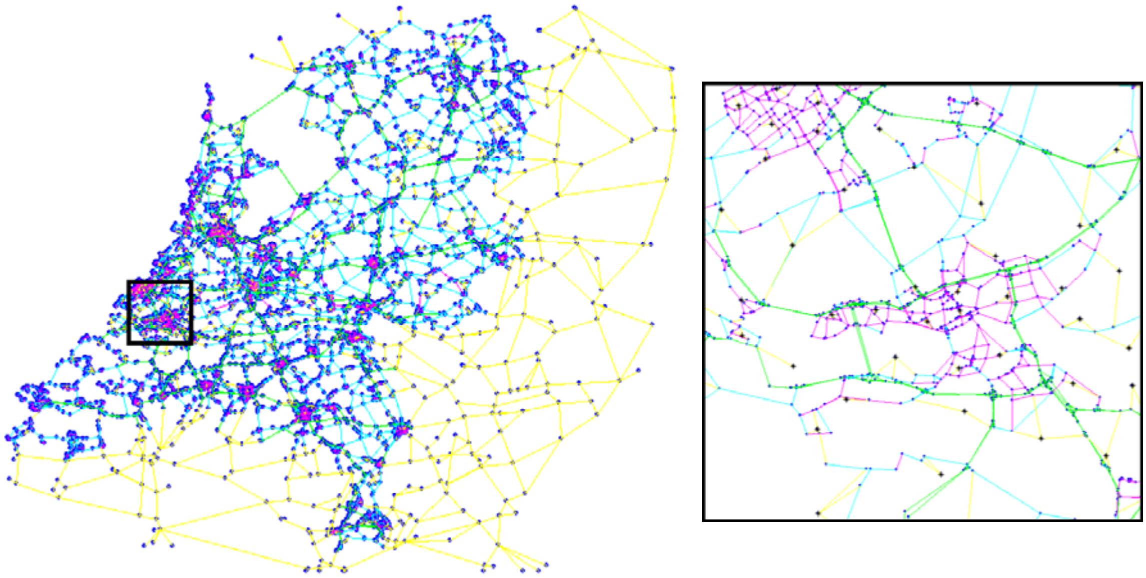

Figure 2: Dutch national network

The time step of the multiclass dynamic network loading model was set to 10 seconds. The total time horizon of the loading model is 28 hours, being 24 hours of demand plus approximately 4 hours of travel time before the last departing vehicle along the longest route completes his trip. This yields more than 10,000 time intervals in the DNL model. An adapted multiclass Smulders' speed-density function is used to compute the link travel times for both user-classes, making sure that their speed is equal in congested situations.

A dynamic network loading on the national network takes between 9 and 16 hours[2], which is 1.8 to 3.1 times faster than real-time, and uses between 880 and 1260 MB of RAM. Only 5 to 10 iterations were necessary for convergence to a stochastic dynamic user-equilibrium solution, due to the fact that apriori route generation is used such that OD flows are distributed already from the first iteration on. The differences in computation time and memory usage depend on the amount of OD pairs with nonzero demand taken into account. Analyzing the travel demand matrix resulted in the observation that 99.9% of the total travel demand is generated by only 66% of the OD pairs. The results of the DNL did not change noticeably when using an accordingly reduced set of OD pairs, whereas the computation time and memory usage decreased dramatically.

From visual inspection we conclude that the assignment outcomes are realistic and that congestion locations are correctly replicated from what is observed in real life.

[2] On a Windows XP machine with Pentium 4, 3.06Ghz, and 2GB RAM.

5 Conclusions and further research

A new analytical DTA model called INDY has been proposed which is truly multiclass and is capable of dealing with large networks, as shown in a numerical example on a large network of The Netherlands. INDY thus overcomes several disadvantages of current analytical DTA models while keeping all of the advantages. At the moment, there is ongoing research on implementing a queuing algorithm into INDY, which will be able to model spillback effects and can handle dynamically changing capacities.

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