Eco-aware Vehicle Routing in Urban Environments

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***Abstract*— Mobility of people and goods in urban environments raises several quality and sustainability concerns. While ICTs have established the ground for developing intelligent transport services, their effective use for supporting cleaner urban mobility still represents a major research challenge. The eCOMPASS research project addressed this challenge through introducing new mobility concepts and establishing a methodological framework for route planning optimization, delivering a comprehensive set of innovative tools and services for end-users to enable *eco-awareness* in urban transport. eCOMPASS innovative tools are based on new algorithmic technology concerning tools and methods for vehicle routing (cars and vehicle fleets) and multimodal human mobility for city dwellers and tourists. eCOMPASS involved a generic architecture that considered all types and scenarios of human and goods mobility in urban environments minimizing their environmental impact. In this work, we report on the main scientific innovations and end-products of eCOMPASS for vehicle routing, including car route planning and vehicle fleets.**

Keywords*— Urban mobility; environmental sustainability; route planning; car navigation; vehicle routing; traffic prediction.

I. INTRODUCTION

The quality of life in urban environments largely depends on the environmental friendliness of human and freight mobility. Intelligent Transportation Systems (ITS) can be applied in support of smart and cleaner urban mobility by improving energy efficiency and reducing CO_2 emissions. This includes new tools and services supporting energy-efficient and environmentally-friendly driving (eco-driving) of both private and freight transportation vehicles. Nowadays, numerous commercial on-board navigator systems provide route recommendations typically minimizing the travel distance or time. Also, sophisticated freight transportation management tools offer trip and distribution planning optimized in terms of cost, time and utilization, while taking important restrictions into account. However, existing approaches neither predict traffic conditions along the planned vehicles' routes, nor they take into account the energy efficiency and environmental impact of transports, especially in urban environments.

Since private car transports are associated with high energy consumption and environmental burden, the role of ICTs in promoting the use of public transportation is critical. Metropolitan public transportation networks tend to grow and densely cover cities, hence, multiple alternatives exist for moving from one point to another; this complicates the use of public means of transport for city residents, even more so for occasional visitors and tourists. To this end, several web/mobile applications exist nowadays for deriving and visualizing routes over public transportation networks, considering all available transport modalities (walking, bus, metro, etc). However, these tools typically derive shortest-path or shortest-time routes and do not take into account alternative objectives, such as recommendation of routes with minimum carbon footprint, minimum number of transfers amongst different means of transportation or minimal use of a specific transportation mode. Furthermore, several extensions on the above public transport route planning features could be investigated. For instance, personalized daily itineraries for visitors and tourists including all sites and attractions which the user would be interested in visiting.

The research project eCOMPASS[1] focused on the aforementioned urban mobility issues through introducing new mobility concepts and establishing a methodological framework for route planning optimization. eCOMPASS delivered an innovative algorithmic machinery which tackles vehicle routing and multimodal (public transit) route planning. eCOMPASS investigated two mobility scenarios with significant share in urban CO_2 emissions: (a) mobility of humans using cars; (b) mobility of goods through fleets of vehicles carrying light or heavy freights. The former has been addressed through intelligent on-board navigator systems that seamlessly provide 'green' route recommendations (minimal environmental footprint and/or fuel consumption). The latter is addressed through the development of a logistics and fleet management system used by human administrators in conjunction with on-board systems mounted on vehicles and used by drivers. In parallel, eCOMPASS developed advanced web and mobile information services that facilitate the use of complex contemporary urban public transportation networks, thereby making inherently 'green' human transports more appealing and usable to urban residents and tourists.

Overall, eCOMPASS delivered four end-products and services, each integrating a substantial core algorithmic component. The end-products broadly split into two main categories, those relevant to *vehicle routing* and those relevant to *multimodal human mobility*. In this work, we report on the main algorithmic innovations and end-products relevant to *vehicle routing*. They consist of:

- A *car navigator* seamlessly offering visualization of computed routes, including alternatives, through familiar on-board navigators. The eCOMPASS car navigator offers two unique features: in-drive alternatives and decide-by-steering. The former visualizes the computation of a network of alternative routes between an origin and destination, determining the relevant alternatives that fork out of the currently followed route; alternative routes that are more economic (wrt fuel) are flagged when the driver approaches the decision point. The latter ensures dynamic system adaptation: the alternative becomes the main route when the driver decides to follow it.
- A *fleet management and trip planning system* including a 'centralized' management system utilized in the headquarter premises of freight transport companies as well as in on-board systems operated by drivers. Key features are the efficient handling of unpredicted events (e.g., ad-hoc orders) and the provision of eco-friendly routes through a novel technique that computes compact and balanced routes.

[1] http://www.ecompass-project.eu/

Our product and services have been successfully validated in extensive pilot tests undertaken in the city of Berlin.

II. Vehicle Routing: Innovations and Services

This section presents the main features of the car navigator and the fleet management system along with the main scientific innovations that established the ground for developing those products.

A. Innovative methods and services for car navigation

A primary goal of eCOMPASS was to leverage the algorithmic advancements made in the project to develop a navigation system tailored for commuters using private vehicles in urban areas making it easier to drive in a fuel-efficient and eco-friendly way. The eCOMPASS user research conducted by TomTom's[2] User eXperience department had revealed that many commuters feel patronized by navigation devices and do not see a benefit in using one on their daily routes[3] albeit state-of-the-art devices effectively help to avoid delays by exploiting traffic information in (re)routing.

Therefore, to make navigation devices more appealing to commuters in the first place, eCOMPASS focused on deriving alternative routes to provide commuters more reasonable route options to compare and to choose from while driving, allowing them to combine and leverage both their expert knowledge of the road network, and traffic information from real-time services. At the heart of the navigation feature lies functionality to compute a network of alternative routes between a driver's origin and destination, yielding a number of "decision points" along each possible route, at which real-time route choices can be made based on up-to-the-minute traffic information (see Figure 1).

To provide route options while driving, TomTom has extended its navigation software stack with a feature called "In-Drive Alternatives". It comprises the background computation of an alternative graph, determining the relevant alternatives that fork out of the currently followed route shortly ahead. Great focus has been put on an unobtrusive UI to display information about these routes just-in-time before a driving decision can be made, and a touchless way to choose the desired route. An example of the UI, when approaching a decision point for an alternative route in the city of Berlin, is depicted in Figure 2. This feature is expected to convince commuters that it makes sense to use a navigation device even in a well-known area in order to avoid traffic jams, to arrive earlier, and to save fuel. Towards the latter, alternative routes that are more economic (in terms of fuel consumption) than the route the driver is currently following are flagged as such when the driver approaches the decision point and the alternative gets offered.

[2] TomTom NV is a Dutch company best known for being a global leader in navigation and mapping products. TomTom has been a partner in the eCOMPASS consortium.

[3] In particular, the following concerns have been voiced: "I know the streets of my city well enough – I don't need navigation to tell me the best route." "I want to know crucial decision points and make my own choices based on current traffic."

Figure 1. An alternative network for a commute in the city of Berlin, Germany, as computed by eCOMPASS algorithms.

Figure 2. Information about an upcoming alternative route in navigator's UI.

The innovative car navigator presented above has been developed on the basis of scientific (algorithmic) innovation with respect to several aspects detailed in the sequel.

Traffic Prediction

Dealing with the problem of traffic prediction is an interesting, yet challenging task, as it needs to cope with the wide variety of different traffic data formats available at each different site. In this respect, one of the primary steps for the application of any prediction technique is the preprocessing of any historical data that may be available, including the tasks of data filtering and cleaning in order to reach a required level of data quality that will positively affect the accuracy of the expected results.

Upon analyzing the problem and describing its variances, we compared different techniques on traffic prediction. The various techniques can be classified into: (a) *Naïve methods,* characterized by the absence of any advanced mathematical model thus comprising simplistic techniques, mainly selected because of their minimum computational requirements; (b) *Parametric techniques,* which are based on specific models, whose general structure and primitives have been defined in advance and only the exact values of their parameters need to be determined on the basis of the available data; (c) *Non-parametric techniques,* which typically fail to presuppose a particular model structure, hence both the exact model structure and its parameters need to be specified from the training data; (d) *Hybrid methods* that exploit the advantages of both parametric and non-parametric techniques.

In eCOMPASS we have developed an original parametric model, called *Lag-STARIMA* [2] that we compared to a set of known techniques, one of which (non-parametric) comprises an original development within the project. Our goal was to leverage on the advantages of both parametric and non-parametric techniques resulting in a variety of solutions that could be used under any possible situation. Based on previous experience, the success of each applied technique depends on the type of data available in any case. The traffic data sets that we used for training and testing the eCOMPASS traffic prediction algorithms, provided by eCOMPASS partner TomTom, includes *speed probes* (instantaneous speeds matched to map links) that were collected from GPS-enabled devices for a total period of two weeks in the city of Berlin.

Lag-STARIMA proposes a parametric mathematical model that comes from the area of time-series analysis. The goal is to compute the parameters of the selected mathematical models so that they describe as accurately as possible the evolution of real traffic over time. One such model is constructed for each individual road of the whole network. The key challenge in Lag-STARIMA is how to properly select the neighbouring roads that participate in each model. Also, the time difference, i.e. lag, of the selected roads plays an important role in the accuracy of the model. To this end, we calculate the correlations of all roads to each other by applying an appropriate correlation metric, the coefficient of determination (CoD), and select the most correlated roads to the road in question. Further improvements of Lag-STARIMA that we achieved on the course of the project include the selection of small regions within the city, based on the network topology, enabling a more efficient calculation of CoD, as well as the calculation of different mathematical models for different periods within the same day, depending on the traffic status, e.g. free-flow vs. congestion.

In order to evaluate the performance of the Lag-STARIMA traffic prediction algorithm we setup a benchmark environment of four known and one new technique. These include Random Forests, *k*-Nearest Neighbour, Historic Average, STARIMA and a data clustering-based technique. Across all of them Lag-STARIMA exhibits the best performance, except for some limited time periods to which the clustering-based approach performs better. Based on our benchmark setup we proposed a hybrid solution so as to obtain the best possible accuracy given the dataset in our disposition. The minimum value of the round mean square error of the estimated travel time that we noticed was around 2 minutes.

Time-Dependent Shortest Travel-Time Routing

The main issue of car route planning in road networks is that the travel-time for traversing a road segment depends on the temporal traffic conditions while traversing it. Consequently, the optimal origin-destination route may vary with the departure-time from the origin. Apart from the theoretical challenge, the time-dependent model is also much more appropriate with respect to the historic traffic data that the route planning vendors have to digest, in order to provide their customers with fast route plans. For example, TomTom's

LiveTraffic service[4] provides real-time estimations of average travel-time values, collected by periodically sampling the average speed of each road segment in a city, using the connected cars to the service as sampling devices. The main challenge is how to exploit all this historic traffic information in order to *efficiently* provide route plans that will adapt to the departure-time from the origin. A customary way towards this direction is to consider the continuous piecewise linear interpolants of these sample points as *arc-travel-time functions* of the corresponding instance. Figure 3 provides samples of such temporal characteristics aggregated by a large collection of historic traffic data that TomTom collected for Berlin.

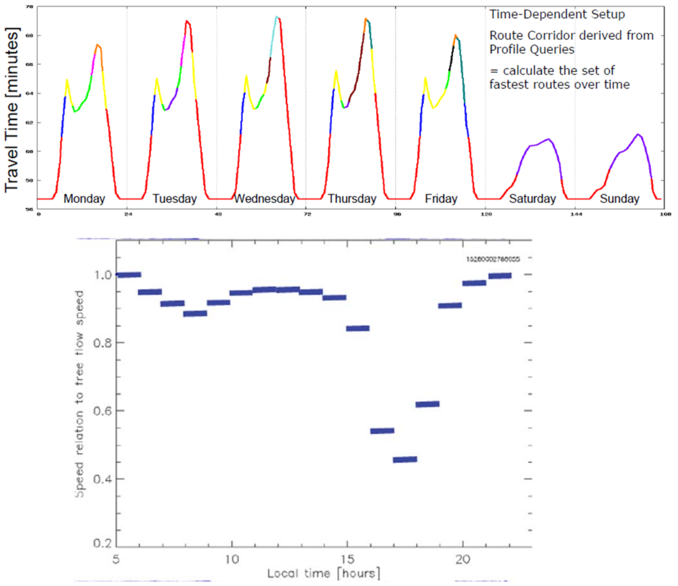
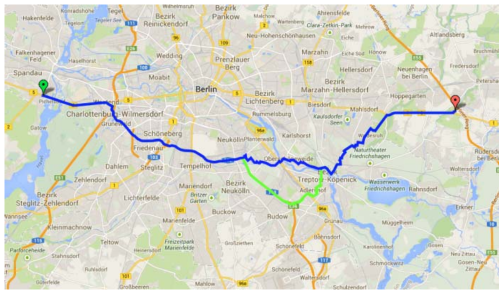


Figure 3: Temporal traffic (travel-time) data per road segment, aggregated by TomTom for the city of Berlin.

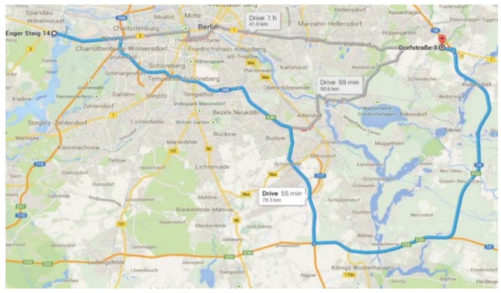
Providing shortest travel-time route plans in time-dependent urban-traffic networks poses new algorithmic challenges. Computing exact solutions is a hard problem, requiring response times of hundreds of milliseconds, or even seconds, per request. Therefore, in order to achieve real-time (within less than a millisecond) responses to queries, we provided the following within eCOMPASS [6]:

- Two efficient algorithms for approximating shortest travel-time functions in urban-traffic networks with time-dependent traffic data for private cars.
- Several landmark-based data structures, precomputed in an offline fashion, that provide urban-traffic metadata (*travel-time summaries*) from suitably selected points (*landmarks*) to all possible destinations in the network.
- Three route-planning (a.k.a. query) algorithms which provide extremely accurate (indeed, exact in almost all cases) time-dependent route plans.

All these novel algorithms and techniques [6] have been analysed, developed, and integrated in a *TD-Route Planner* prototype. We conducted extensive experimental evaluation of this prototype on the benchmark time-dependent traffic data for the city of Berlin [5], with impressive performance both on the efficiency of the preprocessed data (e.g., updating of the landmark summaries towards all destinations in less than a minute), and real-time responses to arbitrary route plans (i.e., in less than 1 millisecond). Figure 4 demonstrates the outcome of our prototype for a given query along with the response of the Google Maps service for the same query.



(a)



(b)

Figure 4: Outcome of our TD-Route Planner (a) and the Google Maps (b), for a given query for the city of Berlin.

As it can be easily noticed, for the same pair of origin and destination, the Google Maps service returned the same (highly suboptimal) route, independently of the departure time from the origin. On the other hand, our TD-Route Planner returned the optimal routes, which differ according to the departure time (early morning or rush hour).

Fast, Dynamic Highly User-Configurable Route Planning

Road networks are commonly formalized as weighted graphs and hence optimal routes correspond to shortest paths in such graphs. In our setting, the environmental impact of a vehicle must be taken into account when determining the graph weights. For example, roads with a lower driving speed are generally more eco-friendly as vehicles consume less energy when traversing them. However, different types of vehicles have different energy consumption profiles (e.g., electric cars can recuperate when going downhill whereas a combustion-based vehicle cannot). Yet, users have very specific and personalized requirements and preferences, and solely optimizing travel time or eco-friendliness with regard to their car model will not be favourable for them. Hence, maintaining a *user-specific personal shortest path metric* is required. Indeed, this can easily be achieved by adjusting the graph's weights according to preference.

Unfortunately, road graphs tend to be huge in practice with vertex counts in the tens of millions, rendering Dijkstra's

[4] http://www.tomtom.com/livetraffic/

algorithm inapplicable for interactive use: It needs several seconds of running time for a single path query. For practical performance on large road networks, preprocessing techniques that augment the network with auxiliary data in an (expensive) offline phase have proven useful. Among the most successful techniques are Contraction Hierarchies (CH), which have been utilized in many scenarios. However, their preprocessing is in general metric-dependent, e.g., the graph metric need to be known apriori. Substantial changes to the metric, e.g., due to the varying environmental impact of the vehicles, may require expensive re-computation.

For this reason, a *Customizable Route Planning* (CRP) approach [1,3] has been adopted within eCOMPASS. It works in three phases (see Figure 5):

- In a first (expensive) phase, auxiliary data are computed that solely exploit the topological structure of the network, disregarding its metric.
- In a second much inexpensive phase, these auxiliary data are *customized* to the specific metric.
- In a last phase, we provide route planning algorithms, responding to arbitrary queries in real-time.

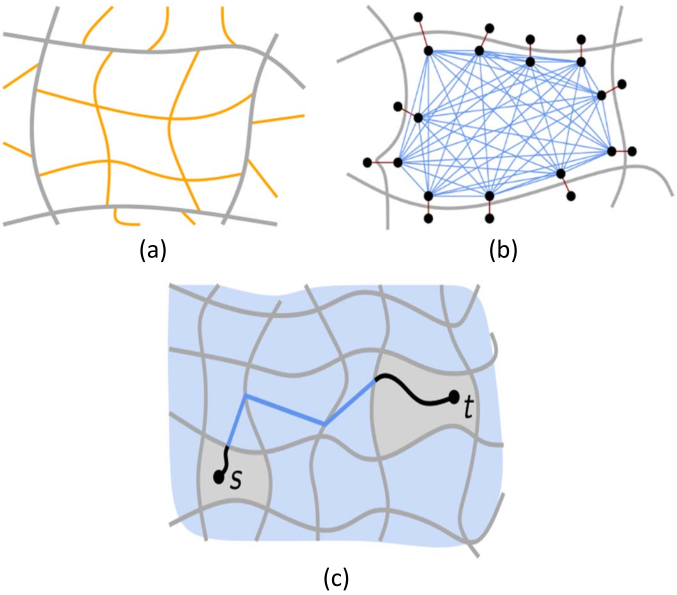


Figure 5: Main phases of the Dynamic, Customizable Route Planning service.

Alternative Routes

Route planners as well as the vast majority of route planning algorithms, typically offer a best route from a source (origin) to a target (destination), under a single criterion (usually distance or time). Quite often, however, computing only one such route may not be sufficient, since humans would like to have choices and every human has also his/her own preferences. These preferences may well vary and depend on specialized knowledge or subjective criteria (like or dislike certain part of a road), which are not always practical or easy to obtain and/or estimate on a daily basis. Therefore, a route planning system offering a set of good/reasonable alternatives can hope that (at least) one of them can satisfy the user, and vice versa, the user can have them as back-up choices for altering his/her route in case of emergent traffic conditions (like traffic jams, accidents, or unavailability due to construction work). The aggregation of alternative paths between a source and a target can be captured by the concept of the *Alternative Graph* (AG). Storing paths in such a graph makes sense, because in general alternative paths may share common nodes and edges. Furthermore, their subpaths may be combined to form new alternative paths.

In general, there may be several alternative paths from the source to the target. Hence, there is a need for filtering and rating all alternatives, based on certain *quality criteria*. The quality characteristics of an AG are captured by three criteria. These concern the *non-overlappingness* and the *stretch* (closeness to optimality) of the routes, as well as the *size* (sum of node out-degrees) in AG. All of them together are important in order to produce a high-quality AG. However, optimizing a simple objective function combining just any two of them is already a computationally hard (NP-hard) problem. Hence, one has to concentrate on heuristics. The most popular heuristic approaches in the literature are based on the so-called techniques *Plateau* (determining the longest possible common shortest routes *from* the origin and *to* the destination) and *Penalty* (penalizing iteratively already computed shortest origin-destination routes), and combinations of them.

In eCOMPASS, we present improved methods for computing a set of alternative origin-destination routes in road networks in the form of an AG, which appears to be more suitable for practical navigation systems [7]. The resulting AGs are characterized by minimum *path overlap*, small *stretch* factor, as well as *low size* and *complexity*.

Figure 6: Snapshot of the Alternative Routes prototype.

Our approach [7] improves upon previous ones in two directions. Firstly, we introduced a *pruning stage* that precedes the execution (and is independent) of any heuristic method, thus reducing the search space and hence detecting the nodes on shortest routes much faster. Secondly, we provided several improvements on both the *Plateau* and *Penalty* methods. In particular, we used a different approach for filtering plateaus in order to identify the best plateaus that will eventually produce the most qualitative alternative routes, in terms of minimum overlapping and stretch. We also introduced a practical and well-performed combination of the Plateau and Penalty methods with tighter lower-bounding based heuristics. This has the additional advantage that the lower bounds remain valid for use even when the edge costs are increased (without requiring new preprocessing), and hence are useful in dynamic environments where the travel time may be increased, for instance, due to traffic jams. Finally, we conducted an experimental study for verifying our methods on several road networks of Western Europe, including Berlin (eCOMPASS pilot site). Our experiments showed that our methods can produce AGs of high quality pretty fast. Figure 6 demonstrates an AG for Berlin.

B. Innovative methods and services for Vehicle Routing

The Vehicle Routing Problem (VRP) is ubiquitous in logistics. Many variations of the original problem have been introduced in the literature and there is a variety of methods to tackle the problem. VRP is a generalization of the Travelling Salesman Problem, known to be NP-Hard, implying that it is unlikely that exact solutions to real life instances of the VRP can be computed fast. The most common ways of overcoming this hurdle is by using heuristics, metaheuristics and approximation algorithms. Many heuristics and metaheuristics have been used to solve variants of VRP. VRP with Time Windows (VRPTW) is a variation that captures real world applications, since each customer expects to be served during a specific time interval. Although VRPTW has been extensively studied in the past, little has been done regarding the computation of eco-friendly routes or taking into account eco-friendly criteria. Towards providing more eco-friendly solutions, the industrial logistics sector has shown a growing interest for solving VRPTW by creating *balanced* and *compact* clusters. Customers are grouped together forming *clusters* that have the same total demand, thus achieving *balance*. A vehicle must be able to serve all customers that belong to the same cluster, thus achieving *compactness*. This approach provides fairness, since all drivers have the same workload to deal with and it is more eco-friendly since the clusters that are created have the property that all their customers are close together and have compatible time windows. Hence, a vehicle can serve them without wasting time going back and forth to the depot.

The solution of VRP/VRPTW by providing balanced and compact clusters is a challenging problem and is partially addressed in the literature. One approach is a modification of the well-known *k-means* algorithm to create clusters of customers, adopting a *two-phase* algorithm that creates connected and balanced clusters. The first phase is a construction phase and the second one is an improvement phase. The connectivity requirement is met by creating a spanning tree in each cluster and the balance requirement is met by maintaining roughly the same number of customers for each cluster. However, this approach does not consider time windows. To take time windows into account, a different algorithm has been suggested that consists of three phases, introducing a Mixed Integer Linear Program (MILP) for solving VRPTW. Since the model can solve small instances (up to 25 customers) typically a clustering method is adopted. In a first phase feasible clusters are identified, in a second phase clusters are assigned to vehicles using the MILP, and in a third phase the VRPTW is solved for every cluster created. This approach, however, does not provide balanced clusters.

Within eCOMPASS we provided a new heuristic approach for solving VRPTW [4], by delivering both compact and balanced clusters of customers, consisting of three phases. First it creates clusters of customers that have compatible time windows. Then it creates clusters of customers that are geographically close together. After the clusters are created, a third (*refinement*) phase takes place. During the refinement phase clusters are merged together, if this is feasible, or split further if they need to. For example, if there are two clusters with compatible time windows and are also geographically close, they are merged into one cluster. On the contrary, if there is a cluster that has customers that are geographically close but their time windows are not compatible it is split into smaller clusters. Our approach [4] delivers a baseline solution which turns out to be rather robust when used in an online environment, e.g., when small changes occur to the (initially computed) tour. In particular, clusters allow us to fit an extra unplanned delivery easily within a cluster. Likewise, if a customer cancels his order, we find the cluster that this customer belongs to and drop him out. Hence, our approach is beneficial in a dynamic setting, since it does not require an execution from scratch.

III. Conclusions

eCOMPASS main scientific innovations and services contributed substantially towards eco-aware vehicle routing in urban environments. Their success was based on significant algorithmic advances, resulting in services that provide several new features compared to other state-of-the-art competitors.

Acknowledgement

This work has been supported by the EU FP7/2007-2013 Programme under grant agreement no. 288094 (eCOMPASS).

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