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16. ABSTRACT

This report describes the results of a project that was initiated under the California-France cooperative research program “CalFrance”, aimed at identifying compatible research interests among researchers in California and France that could be capitalized upon for future larger research projects. In this way, the small investment of seed resources by the California and French governments could potentially leverage significantly larger resources for future work that would benefit both governments.

The Californian and French members of the research teams exchanged technical documents and held seminars and more informal meetings during the project period. It became evident from the shared information, that although they were both working on probe vehicle data collection and analysis, they were starting from the opposite ends of the spectrum in probe data studies. The California probe work has concentrated on arterial applications where very detailed data are needed to support more intelligent traffic signal control strategies, where the latency times are critical. In contrast, the French probe work has concentrated on highway applications with low density data for use in traveler information systems, where the latency times are not nearly as critical. The French work has also concentrated on applications of high-powered mathematical methods for data analysis, while the California work has been based on simple but practical data aggregation techniques.

Due to large differences in the technical approaches taken to date and in the underlying probe data sampling environments, the project partners did not find an immediate target project or technical topic for a larger and more integrated collaborative research project. They agreed that they should remain alert for future chances to work together on probe data analysis and for projects at the U.S. Department of Transportation (DOT) and European Commission levels that could support such work.

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PROBEX: Data Exchanges for Enhanced Traffic Reconstruction

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1. Background

The PROBEX project was initiated under the California-France cooperative research program “CalFrance”, aimed at identifying compatible research interests among researchers in California and France that could be capitalized upon for future larger research projects, especially those that could be funded at higher levels of government (U.S. DOT and European Commission). In this way, the small investment of seed resources by the California and French governments could potentially leverage significantly larger resources for future work that would benefit both governments.

The PROBEX project was conceived by researchers at the California PATH Program in Berkeley and at Mines-Paris Tech in France, a joint research enterprise of several important research institutes near Paris, including the Ecole des Mines and INRIA. The original plan for the project involved seminars to be held between the research teams in both California and France, but this was not possible when the travel funds were eliminated from the California project. Eventually, the seminars were held only in California, facilitated by the fact that one of the key members of the French team, Prof. Fabien Moutarde, had a three-month visiting appointment in Berkeley during the project period of performance, but for a different project. Although the other project consumed the large majority of his attention, it was still possible to exchange ideas and information about PROBEX, and since the other project was on a related topic there was some synergy with that work.

2. Primary Findings

As the Californian and French members of the research teams exchanged technical documents and held their seminars and more informal meetings during the project, it became evident that although we were both working on probe vehicle data collection and analysis, we were starting from the opposite ends of the spectrum in probe data studies. The California probe work has concentrated on arterial applications where very detailed data are needed to support more intelligent traffic signal control strategies, with fine spatial resolution and low latency. In contrast, the French probe work has concentrated on highway applications with low density data for use in traveler information systems, where the latency times are not nearly as critical. The French work has also concentrated on applications of high-powered mathematical methods for data analysis, while the California work has been based on simple but practical data aggregation techniques.

Over the course of the project, the work on the French side evolved to come somewhat closer to the California work, with increasing attention to arterial applications. This may have been motivated in part by Prof. Moutarde’s work with Prof. Alex Bayen in Berkeley on the Connected Corridors project, which is covering both highways and arterials. Both the French and Californian project members became increasingly interested in the opportunities for fusion of probe data with data from fixed detectors, which has very different properties. This fusion can be very effective during the early years of probe data system deployment, when the market penetration of probe vehicles is still low.

The French team discovered the need for high-fidelity microsimulations of traffic conditions to test probe sampling strategies and to provide a baseline “truth” model for comparison with probe-based estimates of traffic conditions. Prof. Moutarde spent a significant effort learning about the PATH microsimulation models of the El Camino Real corridor in VISSIM and the I-80 corridor in Aimsun, and PATH offered him use of both of these models to support his planned studies. In the end, the linkage between the projects came through Prof. Bayen’s French doctoral student, Aude Hofleitner, who was working closely with Prof. Moutarde and considering use of one of the PATH simulations for the final verification stage of her thesis.

Some underlying differences continue to represent challenges to closer integration of the probe data studies in California and France. In France, the probe sampling is expected to be occurring at large time and distance intervals, and the samples will be collected over existing cellular data networks. By contrast, the California probe studies have been considering much higher density sampling in urban and suburban arterial networks, with the data being uploaded when the probe vehicles arrive at 5.9 GHz DSRC hot spots.

The report by Prof. Moutarde on his stay in Berkeley (attached as Appendix D) deals with a highly aggregated use of probe data to assess the relative connectedness of sub-networks within a larger transportation network (such as neighborhoods within San Francisco). In order to do this type of study, it is necessary for the probe vehicle trajectories to be linked more or less from origin to destination. This type of linkage violates the privacy principles that were established for connected vehicle projects in the U.S., since it could theoretically enable somebody to mine the full body of probe data to identify the trajectory of an individual traveler. Consequently, this type of probe data use would probably not be permitted in the U.S.

These large differences make it hard to apply the same technical approaches to aggregation and analysis of the data in both places.

Prof. Moutarde and his colleagues, together with members of Alex Bayen’s group presented a paper about their work at the 2012 TRB Annual Meeting:

"Large scale estimation of arterial traffic and structural analysis of traffic patterns using probe vehicles", Aude Hofleitner, Ryan Herring, Alexandre Bayen, Yufei Han, Fabien Moutarde and Arnaud de la Fortelle, Transportation Research Board 91st Annual Meeting (TRB 2012), Washington DC (USA), 22-26 January 2012.

3. Future Opportunities

Considering the large differences in the technical approaches taken to date and in the underlying probe data sampling environments, the project partners did not find an immediate target project or technical topic for a larger and more integrated collaborative research project. They agreed that they should remain alert for future chances to work together on probe data analysis and for projects at the U.S. DOT and European Commission levels that could support such work.

The project partners also saw opportunities for future work on the fusion of probe data with data from fixed traffic detectors, since this requires some more fundamental data analysis research. This is already an element in PATH's Exploratory Advanced Research Project on Advanced Traffic Signal Control Algorithms, but that project is expected to end at the end of 2012, so it does not provide a long-term basis for collaboration.

4. Appendices

A. Summaries of Existing Projects Related to Probe Vehicle Data

B. Minutes of First Probex Workshop

C. Minutes of Second Probex Workshop

D. Report on Traffic Simulation Tools and Traffic Mining and Modeling Algorithms for Management of Large Networked Corridors by Fabien Moutarde (report on his visit in Berkeley)

Appendix A:

PROBEX Project:

Summaries of Existing Projects Related to Probe Vehicle Data

Prior and current projects at PATH related to probe vehicles and traffic data

- The PATH probe vehicle studies have been based on the federal IntelliDrive (now connected vehicles) program, assuming the use of DSRC for V2I probe data communication, with a high market penetration of equipped vehicles. Under the federal program, a specific set of probe data sampling rules was developed and embedded into a standard by the Society of Automotive Engineers (SAE J2735).
- Motivation for probe vehicle data collection is to get traffic information on arterial/local streets, where limited or no loop data is available, and to get information which is both complementary (travel times rather than local speed/throughput) and richer (cf. air temperature, wipers and fog lamps status, etc., which might be transmitted as well, through the OBD-II access to CAN data). In the long term, probe data could potentially replace magnetic loops if the results of the probe data analyses are sufficiently favorable..
- The SAE J2735 probe sampling rules have a lot of details that are intended to minimize the amount of data that needs to be communicated while maximizing the protection of privacy to travelers, within the constraints of the original IntelliDrive architecture. These rules tend to reduce efficiency of the data collection and make the data difficult to use for traffic state reconstruction, because they are founded on the architectural assumption that all raw vehicle data would be channeled into the backhaul network for data mining by the end users. As the connected vehicles program evolves, this architecture is likely to change, with the opportunity for local data aggregation to protect privacy.
- The PATH simulation-based probe vehicle studies have shown the limitations of the specific probe sampling strategies of SAE J2735 and have led to recommendations for some changes to those strategies. Among the many problems, there can be 600 vehicles within range of a given RSU, each sending 500 B/s of data, so a total of up to 300 KB/s of data would have to be sent by each RSU. The PATH recommendations are based on general applications-oriented requirements, which are different for highway traffic, arterial traffic, incident detection, weather conditions and road surface state.
- PATH has done a small probe sampling study for Toyota InfoTechnology Center, using a simplified microsimulation of a hypothetical freeway corridor to provide the baseline truth data for an evaluation of a clustering strategy proposed by one of the Toyota researchers. This is based on the desire to minimize the rate of data communication from the probe vehicles to the roadside, at the cost of increasing the V2V communication used to cluster the vehicles for local data aggregation.

- The current PATH probe data sampling research is being done under the FHWA Exploratory Advanced Research Program project on Advanced Traffic Control Algorithms, which are being designed based on the availability of probe data in urban signalized arterial networks. In this project, the prior VISSIM simulation of El Camino Real is being used to support estimates of a variety of intersection control measures of effectiveness, and for fusion with traffic detector data in order to provide improved value at very low probe market penetrations. This has been found necessary in order to obtain sufficient data to be applicable within short enough latencies to be useful for adjusting traffic signal control strategies.

Prior and current projects at LaRA (= CAOR/MinesParisTech+INRIA-IMARA)

- Prior experience with probe vehicle concepts in Europe was developed in the REACT project (black ice detection information relayed to other vehicles), Com2React project (virtual sub centers representing clusters of vehicles), and GeoNet project (standardization for geographical referencing in ETSI and ISO).
- Current probe projects in LaRA are PUMAS and Travesti, subjects for direct interaction with PROBEX. Key topics in these include field testing with 1000 fleet vehicles in Rouen (Normandy), equipped with special OBUs sending travel times, and possibly other proprioceptive information. One of the difficulties is the probable sampling biases due to peculiarities of private fleets of vehicles (not using the same roads at the same time as most “normal” vehicles). The specific allocation of responsibilities between OBUs and RSUs still needs to be determined.
- PUMAS is the field testing project, using the concept of Virtual Magnetic Loops to indicate between which points the travel times are estimated; note that the data may be uploaded later than the end of Virtual Loop, depending on availability of upload access point.
- Travesti is a simulation-based project to develop methods for reconstructing traffic conditions from the probe samples, using the METROPOLIS mesoscopic simulator.
- The research emphasis in the current projects in LaRA is on developing methods for efficiently extracting traffic condition information from limited numbers of probe vehicles in mid-size cities that do not have extensive infrastructure-based traffic detection systems. This information is expected to be at the level of network travel times that could be used to support traveler information systems rather than at the more microscopic level of resolution that would be needed for traffic signal control systems.
- The traffic state reconstruction approach developed by LaRA is based on discrete rather than continuous variables, focusing on the probability of a link being in each discrete state, using the Belief Propagation algorithm.
- There has been limited input from the end users in France to guide determination of the application needs for the probe data, but most expected application sites have very limited existing infrastructure and data, so they could benefit from even minor improvements.

Appendix B:

Minutes of First Probex Workshop

Berkeley, January 11, 2012

Steven Shladover represented PATH, and Fabien Moutarde represented Mines Paris Tech.

For this workshop, the focus was on explaining our respective approaches to probe data sampling and the applications that we intend to support with our probe data. We found a large contrast between our applications, which in turn led to substantially different technical approaches.

The Mines Paris Tech work on probe data has been at a highly aggregate level, based on sampling from a limited market penetration on a road network for a medium-size city, to assess long-term trends in traffic conditions for providing general traveler information and off-line planning work. They have been applying very sophisticated mathematic methods of “Belief Propagation”, particularly to deal with situations in which there is no detector data available, but only the limited samples of probe data.

In contrast, the PATH probe work has been focused on the most demanding real-time arterial traffic signal control applications, where it is important to have low latency and high accuracy of probe vehicle data. These have been studied in the context of relatively simple sampling strategies and somewhat more complicated strategies designed for a different purpose in the SAE J2735 standard.

Considerable attention was devoted to the Aimsun simulation that PATH developed on the I-80 corridor for testing variable speed limit and coordinated ramp metering strategies, which could potentially be useful for some of the work that Fabien Moutarde will be doing during his stay in Berkeley.

The discussion advanced toward consideration of the areas of common interest, which appeared to include:

- authoritative data sets to provide truth references for calibration or evaluation of probe data schemes
- fusion of probe vehicle data with other data available from infrastructure-based detectors
- use of traffic simulators as testbeds to evaluate probe approaches prior to field testing
- developing efficient strategies for mining the raw probe data to extract useful information about traffic conditions
- comparing technical strategies for protecting privacy of travelers, within local political constraints
- predicting travel times by combining current probe data with historical data about network performance
- identifying opportunities to work together on a larger project in the future, in which we could actually implement and test the effectiveness of probe strategies.

Appendix C:

Minutes of Second Probex Workshop

Berkeley, March 20, 2012

Steven Shladover represented PATH, Fabien Moutarde represented Mines Paris Tech and they were joined by Aude Hofleitner, a French doctoral candidate studying under Prof. Alex Bayen in Berkeley.

This meeting focused on traffic simulation tools that could be applied to evaluation of probe data collection, since this is a challenge both research teams face. With the evolution of the French team's interests from freeway toward arterial applications, the opportunities for use of the PATH simulation model of El Camino Real to support their work became more important. They would consider this VISSIM simulation as well as another simulation based on Dynus-T from the University of Arizona.

The intended use of the El Camino simulation would be to repeat the simulation runs at a variety of different demand levels, to estimate the relationship between demand level and corridor travel times. This would be the basis for calibrating the probe sampled estimates of traffic volume, which would be done for up to ten demand levels and ten turning ratios.

There was also a connection between these simulation studies and the work that Fabien Moutarde has been doing with Alex Bayen for the Connected Corridors project during his stay in Berkeley, involving fusion of probe and detector data to estimate travel times and speeds. This work is likely to continue even after Fabien returns to France.

Aude Hofleitner has been working on arterial traffic time estimation, but has not been able to progress as far as she hoped based on use of the NGSIM Peachtree St. data set, which covers too short a time and too few vehicles to be useful. She could potentially use the PATH simulation of El Camino to evaluate her estimates of travel times and the arterial fundamental diagram using probe sampling strategies.

Other future opportunities were discussed, including association with a new center of excellence for smart mobility being created in the Paris region, part of a network of seven new national energy-related research centers being funded at a level of €54 million (about \$72 million). In addition, Fabien will be visiting Berkeley in mid-October with a delegation of robotics students from Mines Paris Tech, providing a potential opportunity for further interactions (except that Steve Shladover will be overseas that week).

Appendix D:

**Report on traffic simulation tools and
traffic mining & modeling algorithms
for management of large networked corridors**

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[Appendix A:](#) Analysis of Dynus simulation requirements and capabilities

[Appendix B:](#) Identification of weakly dependent regions in urban networks using partitioning algorithms for tractable traffic estimation and prediction (submitted to ISTTT2013 conference)

[Appendix C:](#) Temporal Analysis of Global Traffic Dynamics using Non-negative Tensor Factorization in large urban networks (submitted to ISTTT2013 conference)

1. Traffic simulation tools for large networked corridor

Integrated Corridor Management (ICM), because it aims at mitigating congestion by influencing users' behaviors, critically needs flexible traffic simulations in order to be able to evaluate, compare and tune various possible traffic management policies.

If one wants those simulations to provide reliable estimations of the impact of actions on traffic, it is necessary that they be as realistic as possible. This implies the necessity to:

- have an accurate model of the network of roads/streets considered in the corridor, including topology (connectivity), capacities (at least number of lanes and free-flow speeds necessary to parameterize traffic flow models), controls (traffic signals, stops, yields, with required associated parameters for the modeling of flows through intersection);
- obtain, or build, some reasonable baseline model of the demand.

For the network model, one first possibility is to build "by hand" in some network editor tool. We first experimented this on the full Peninsula (101-CaminoReal-280) corridor, as reported below.

1.1 TOPL network editor

The online current version of TOPL's "Network Editor" provides a rather convenient way of semi-automated manual building of network model. It makes use of GoogleMaps API to automatically build between 2 nodes a link that follows existing road street, and gets correct name and length. As a test, we decided to begin manual design of Peninsula corridor with this tool, and the result is shown below on figure 1.

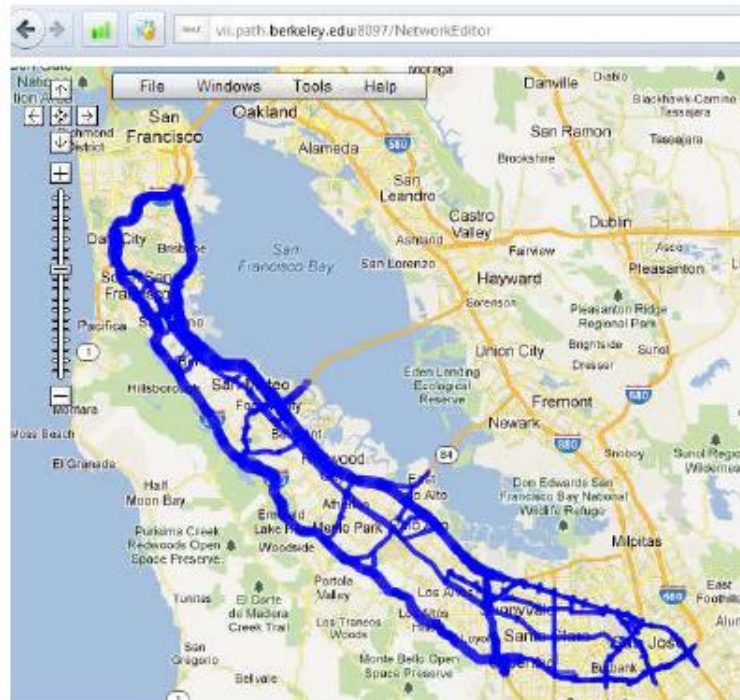


Figure 1. Peninsula corridor full network created with TOPL Network Editor (only links shown; the network has 1189 nodes and 1535 links)

One of the needs encountered was the possibility to crop a sub-part of an existing TOPL network. *We have thus developed and tested a simple Matlab cropping tool that, given a square region defined by minimum and maximum longitudes and latitudes and a TOPL network XML file, generates a new TOPL network XML file with only nodes/sensors/controls inside the sub-region, and only the links entirely in bounding-box (i.e. whose both extremity nodes are kept).* A result with cropped upper-mid Peninsula sub-network (bounded on north by I-380, on west by I-280, on east by I-101 and on south slightly below SR-92) is shown below on figure 2.

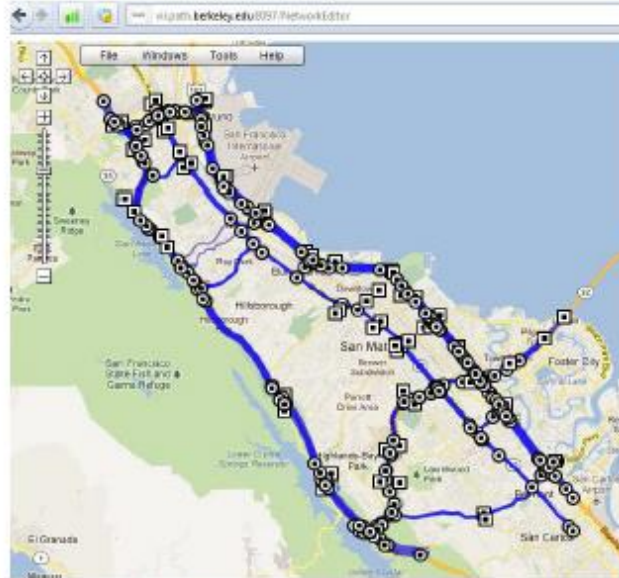


Figure 2. Peninsula corridor upper-mid sub-network in TOPL Network Editor, (314 nodes and 432 links) obtained by cropping the full network

Lessons learnt from building that large network with TOPL current Network Editor

An unfortunate drawback of the current version of this tool is that it currently does NOT automatically set the type of link (freeway v.s. on-/off-ramp v.s. arterial), so this has to be set manually through the GUI, which is rather tedious for large network. *Even more annoying is the fact that the number of lanes on links, quite crucial for any simulation, also has to be set manually, by zooming on GoogleMaps satellite view and visually counting the lanes: this is definitely overwhelmingly time-consuming, rather error-prone, and could probably be automated in some way, either by integration with queries on Navteq or other cartography, or even by some vision-based lane-counting algorithm.*

The type of traffic control at nodes (none v.s. traffic signal v.s. stop v.s. yield) also needs to be manually specified if one wants it to be exact. The only way an automation improvement could be done for this is by extracting the information from some GPS navigation cartography.

The global conclusion is that it is highly desirable to craft an “importation tool” allowing extraction of all relevant roads/streets network information from existing sources such as GPS cartographies or GIS for planning softwares.

1.2 Network importation in DynusT

The DynusT simulation software includes interesting functionalities currently not (yet ?) implemented in TOPL tool:

- Dynamic Traffic Assignment (DTA) allowing to deduce (guess ?) the flows in the network from the demand expressed in the form of Origin-Destination matrix;
- built-in simulation of ramp-metering or diversion (mandatory or suggested) through VMS;
- built-in ability to simulate that a given proportion of users can choose their route at departure time after consulting pre-trip traffic information, and another proportion can even dynamically re-route along their trip, according to en-route traffic information

Together with the fact that it is an open-source freeware, that can therefore be obtained at no cost, and could if necessary be modified to incorporate simulation of more advanced influence on users' behaviors, this motivated us to also experiment this traffic simulation tool.

Manual editing of the network in DynusT is totally unaided/un-automated, so from this point of view it is clearly worse than TOPL. On the other hand, DynusT provides rather convenient ways to import most network information from external source. We have exploited and tested this last feature by writing a conversion filter for producing, from any existing TOPL network in XML format, the import data required by DynusT. With this tool we were able to convert our TOPL Peninsula networks into DynusT models, as shown below on figures 3 and 4.

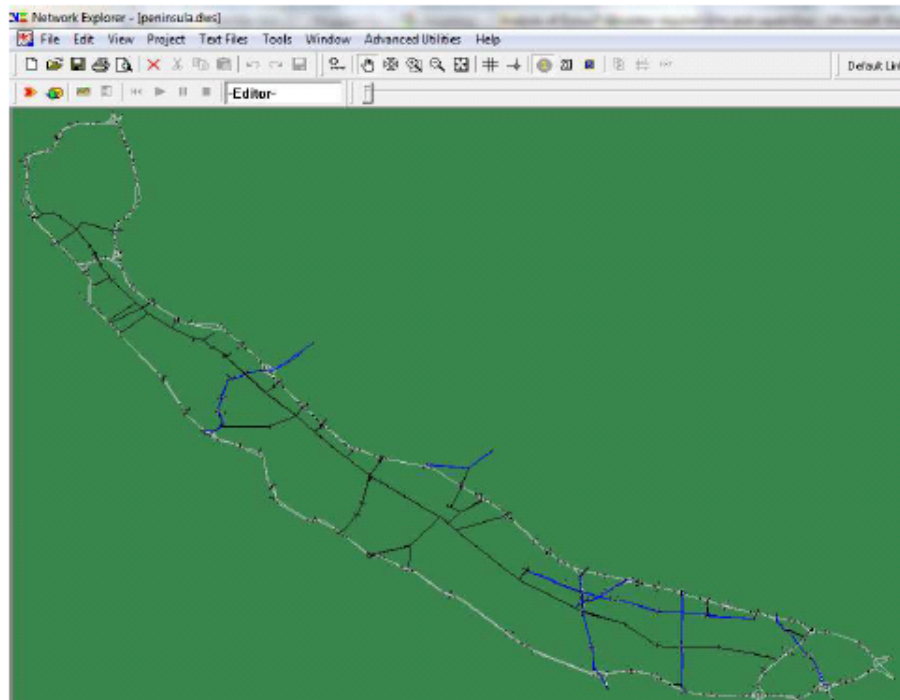


Figure 3. Peninsula full corridor network imported in DynusT
(freeways in white, highways in blue, arterial in black)

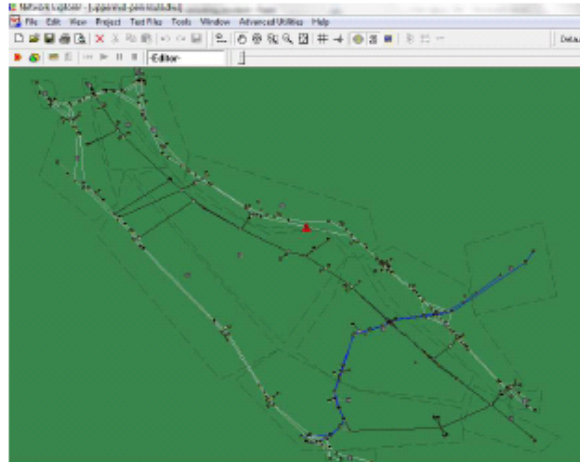


Figure 4. Upper-mid sub-network of Peninsula corridor in DynusT, with manually-defined OD zones.

1.3 Importation of OD zones into DynusT

Since the essential input for running simulations in DynusT is Origin-Destination matrix (possibly several in successive timeslots), it is required to define zones for the OD before any simulation can be launched. For the Peninsula subnet, we have manually defined zones (see above figure 4), just to be able to run some simulations. However, if one wants simulations with traffic flows and geographic patterns close to reality, it is necessary to use some estimated real OD matrix. Such kind of data is provided by MTC for the whole bay area, with origin-destination estimated hourly volumes to/from 1454 Traffic Analysis Zones (TAZ). In order to use this data into DynusT simulations, a first required step is the importation of the 1454 TAZ boundaries. DynusT provides a Zones importation, but only from GEO format, and the 1454 TAZ were found available rather in KML or shape files. We have therefore developed a conversion tool that parses TAZ file in KML format, and generate the equivalent in the internal DynusT text format.

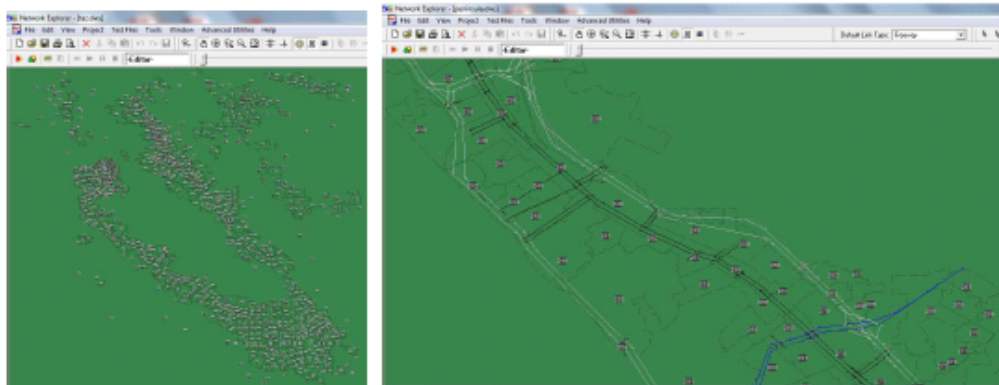


Figure 5. Visualization of MTC's 1454 TAZ after importation into DynusT (left, only the TAZ, over the whole Bay Area; right, zoom on the upper-mid Peninsula subnet with superposed imported TAZ)

A more detailed analysis of DynusT simulation requirement and capabilities, in particular import functionalities, is included in appendix A at the end of this report.

1.4 Simulated Peninsula corridor experiments with DynusT

As a first step in experimenting traffic simulations of a networked corridor, we have used the upper-mid Peninsula sub-network, and DynusT software. Because more work is still needed in order to infer, from MTC's global Bay Area OD matrix, a *local OD restricted to Peninsula* full network or sub-network, we first used a quite rough model of passing-through traffic: using our manually-defined zones (rather than MTC's TAZ), we defined a very rough OD matrix with only flows southbound and northbound flows of vehicles, from/to only 7 outer zones of the upper-mid Peninsula sub-network: 3 north "gates" (101, 280, and CaminoReal), and 4 south "gates" (San Mateo bridge, 101, 280, or CaminoReal). Note that, even with such a crude approach, more realistic demand patterns could probably be approximately inferred from existing information, in particular the very valuable OD estimates provided by MTC for peak traffic on main bridges of the Bay (cf. example shown on figure 6, which is for San Mateo bridge).

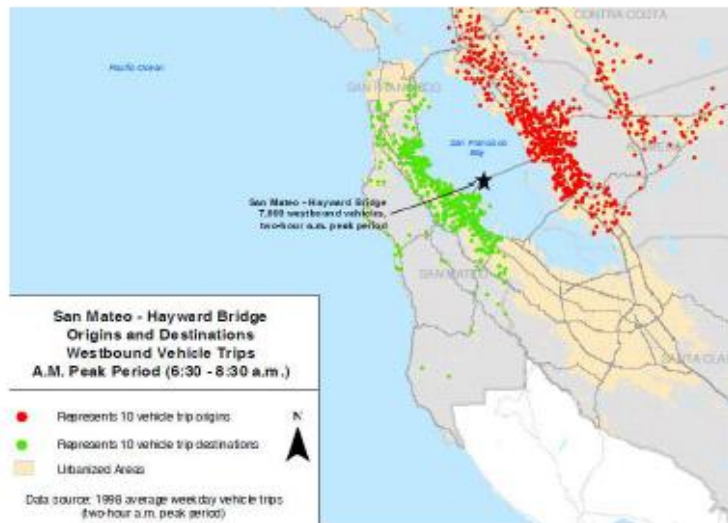


Figure 6. Example of OD data provided by MTC for peak hour traffic over main bridges of the Bay; here, the morning westbound info for San Mateo bridge (therefore, traffic incoming into the corridor)

Given our very simple crude OD, we first ran iterations of Dynus Dynamic Traffic Assignment (DTA), in order to define some baseline routes for ~100,000 vehicles traversing the sub-network during a 5 hour period, with simple scaling of the OD for 5 time-intervals of 1 hour, as can be seen on the departure time pattern on left of figure 7a below. Some of the characteristics of the produced time-varying traffic flows are presented in figures 7a, 7b and 7c below.

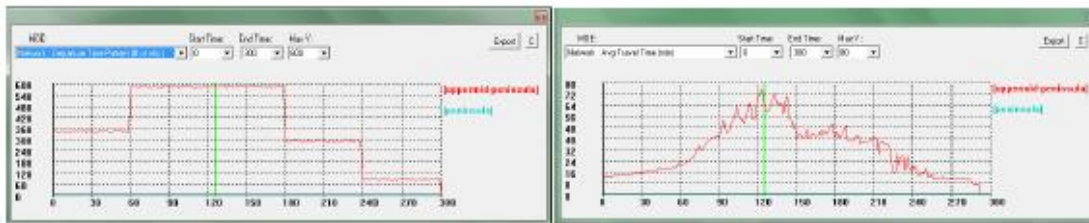


Figure 7.a Departure time volume pattern used in baseline simulation on left; resulting average travel-time time pattern on right.

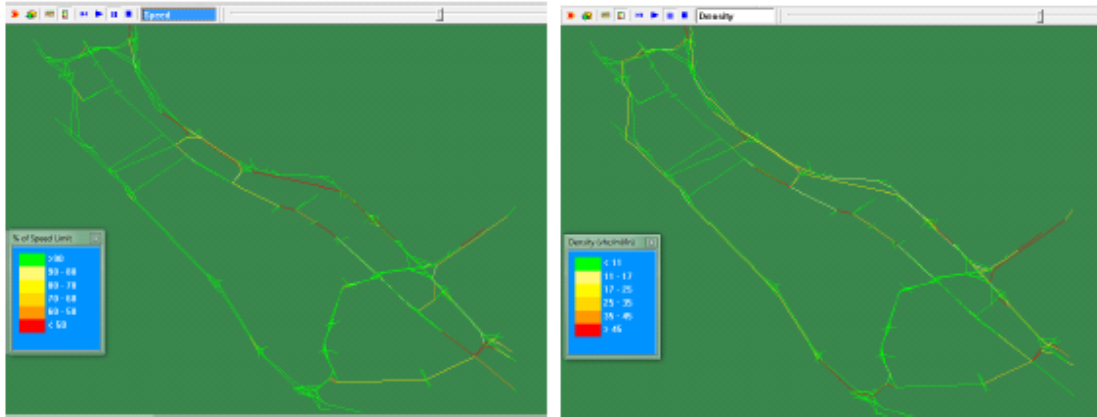


Figure 7.b Resulting baseline peak-hour speed (on left) and density (on right) geographical patterns

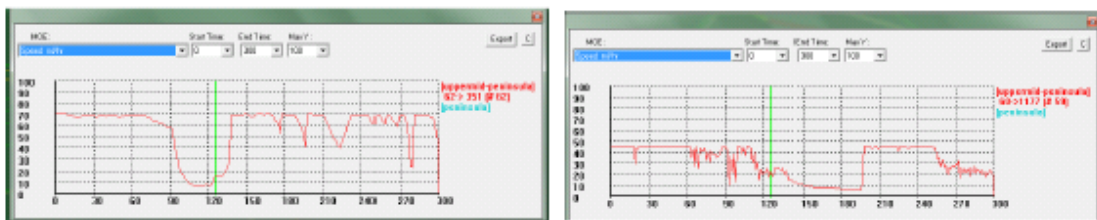


Figure 7.c Resulting typical speed evolution patterns on some links (left, a southbound section of 101; right a southbound section of Camino Real arterial)

The resulting baseline traffic pattern shows some congestion at peak hour, especially on southbound 101 between SFO airport and San Mateo bridge, and on southbound central part of Camino Real arterial, which can be seen on figure 7b. The time evolution patterns of these congestions are illustrated on figure 7c, where one can see in particular a 45mn strong congestion on 101 between during [90;135] time interval.

One of the interesting built-in features of DynusT is the possibility, starting from a one set of vehicle paths corresponding to user-equilibrium of traffic assignment, to simulate various scenarios, such as incidents reducing the capacity of certain links, and then visualize/analyze the impact of the incident on congestion and travel times. In order to experiment this, we have run such a scenario of big incident on southbound 101 between SFO airport and San Mateo bridge. The resulting aggravated congestion pattern is illustrated on figure 8 below.

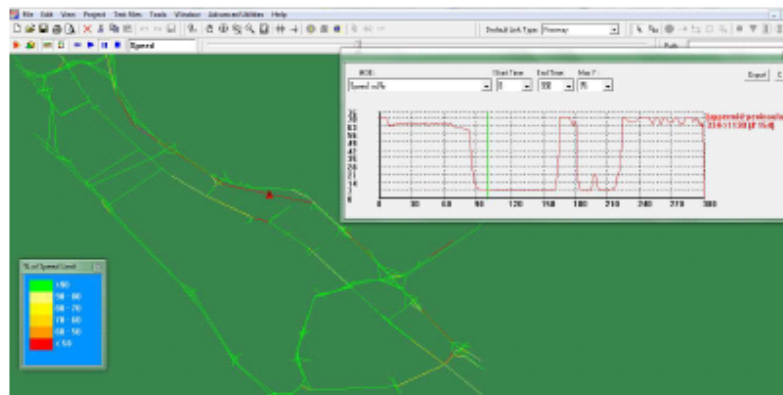


Figure 8. Incident simulation: one can see on the network plot the strong congestion propagated backwards on 101 from the incident location, and the dramatic long traffic jam on speed time plot.

Finally, even more interesting and valuable, *DynusT* also includes built-in functionalities for simulating the effect on traffic of a certain proportion of users choosing their itineraries at departure time, based on pre-trip traffic information. Even more valuable is the possibility to simulate that a fixed proportion of users regularly receiving traffic information and use it to dynamically and individually re-route themselves to alternative path. We have mainly experimented this last functionality, as a first example of studying post-incident re-routing strategies in the Peninsula corridor, and also to analyze the potential effect of massive “selfish” re-routing with traffic-aware GPS device.

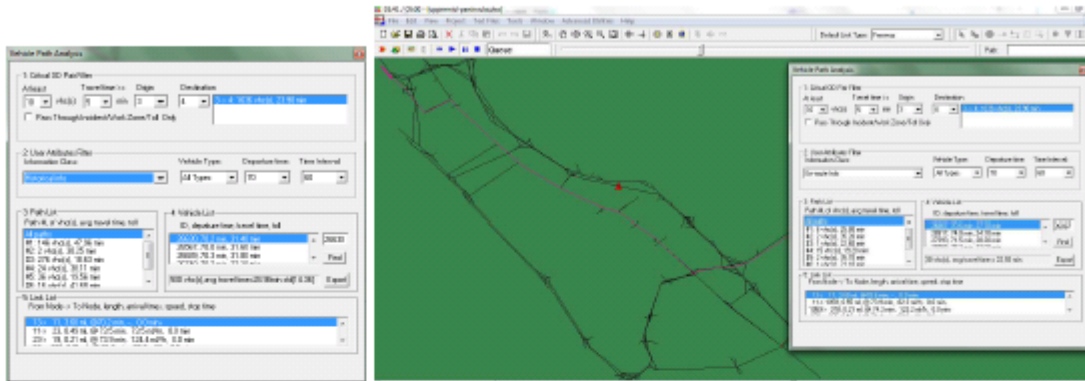


Figure 9. Impact of incident on travel-times of vehicles taking usual path, and typical alternative path taken by users dynamically re-routing using en-route traffic information; note here that the latter get a 6mn=29% gain in average travel-time (23 mn instead of 29mn) from zone3 to zone4 during incident

A quite interesting thing to study is the impact of the proportion of “en route re-routers” on respective and average travel times. As one can see on figure 10, travel time gain for users going from Z3 (northmost 280 entry point) to Z4 (San Mateo bridge) remains significant (11% to 29%) when proportion of “re-routers” stays below 40%. However, when the penetration rate of dynamic behavior increases above 50%, the relative advantage of “dynamic re-routers” tends to cancel out. Above 75%, it even seems that dynamically re-routing can lead to longer average trip time, which is probably due to secondary congestion generated by too much traffic on common re-routing path.

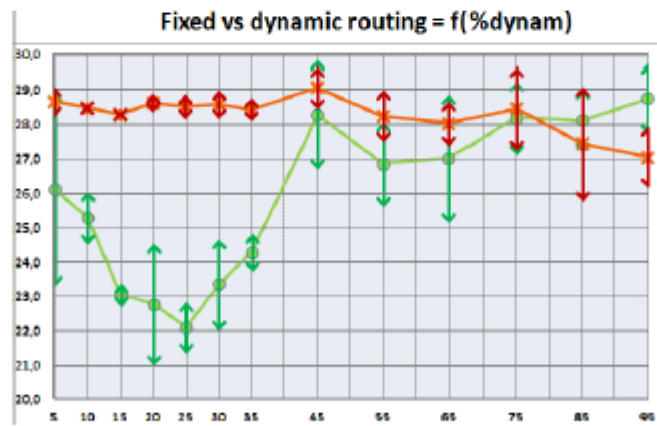


Figure 10. Influence of percentage of “dynamic re-routers” on the respective travel-times of users with a significantly affected OD pair: in green, average trip time for dynamic re-routing users; in red, average travel time for “fixed route users”. A large gain (up to 7mn/29mn=24%) is obtained by dynamic routing, but only when their proportion remains below ~40%.

The ranking inversion of dynamic vs static routing is even clearer on figure 11, where travel times are analyzed for users going from Z1 (north most entry point of 101 in subnetwork) to Z4 (San Mateo bridge), whose route is the most affected by simulated incident. Travel-time gains are significant for re-routers (up to 11mn/68mn=16%) when their proportion remains below 25%, and their re-routing even importantly reduces congestion and travel time for "non-re-routers". However, when penetration rate of dynamical re-routing goes over 35%, the latter begin to experience rather longer travel times than others (up to 10mn/59mn=17%). In fact, there is even a global system optimum, around 33%, for the whole group of users going from Z1 to Z4.

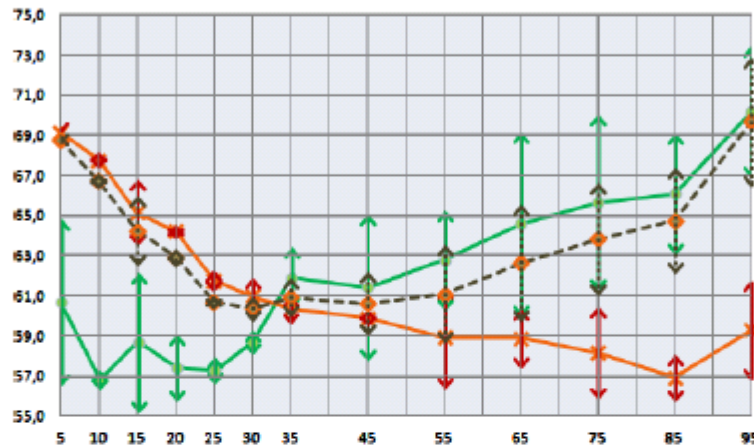


Figure 11. Influence of percentage of "dynamic re-routers" for the most affected OD pair: in green, average trip time for dynamic re-routing users; in red, average travel time for "fixed route users". A significant gain is obtained by dynamic routing only when their proportion remains below ~25%, but the ranking is reversed when more than 35% of users adopt dynamic re-routing. There is visibly a system optimum for that whole group of users (dashed line), around 30-50%.

Note that the above experiment and analysis were conducted for fixed parameters of the dynamic re-routing behavior: namely, comparing current travel-time of a large number (999) of pre-computed possible paths, at a rather high frequency (every 2 mn). It would be worth analyzing how these behavior parameters, especially the frequency, may influence the outcome of dynamic re-routing. Also still to be done is a wider analysis, on a whole set of simulation scenarios, in particular various demand settings, with **and without** severe incident.

Conclusions from these first Peninsula corridor simulation experiments

From the reported above small set of simulation experiments for part of the Peninsula corridor with DynusT software, we already can infer a few lessons:

- First of all, it is feasible, even without a precise OD matrix restricted to the simulated region, to run simulations with reasonable enough flows to conduct some rough tests of Traffic Management strategies, especially for dealing with incidents;
- About Traffic Management strategies, our experiments show the importance of considering the simplest user-centric dynamic re-routing, which is likely to become more widespread as GPS navigation tools (whether dedicated devices, or smart-phone Apps) will increasingly provide such traffic data feeds. Being able to properly simulate individualized re-routing behaviors should be a strong requirement for the final simulation tool to be used in the ICM project.
- Even if our set of simulation experiments was very small, so it may be risky to infer general conclusions from them, we have shown that at least in some traffic settings (severe incident at peak hour on critical freeway), inciting a significant proportion of road users to use simple "selfish" dynamic re-routing can not only save those drivers some travel time, but even globally decrease congestion. However our simulations also shows that there could be a global optimum interval for the proportion of "dynamic re-routers", and their individual travel times, as well as global congestion, can in fact get WORSE if too large a proportion of drivers apply this strategy.
- On the methodology and tools point of view, it is important to be aware of the significant randomness that arises in traffic outcome, so any result MUST be evaluated with ENOUGH random realizations of same simulation settings, so as to estimate the variance, which can be quite high. Also, most traffic management strategies have at least several parameters that can strongly influence their outcome. All this points to the necessity, for the simulations tools to be used in ICM project, to include (or at least permit) scripting facilities, so as to be able to easily launch large number of simulations, and collect/aggregate their results.

2. Traffic-mining and modeling algorithms

The more “academic-research oriented” part of our work during our visiting research period at Berkeley CCIT was focused on traffic-mining and modeling algorithms. The reported research works were collaborative research with several of the CCIT PhD students and post-docs.

2.1 Partitioning a traffic network in weakly-dependant subnets

When handling a rather large network of roads and streets, an important issue is that it might be too large for traffic analysis and forecasting to be properly and efficiently handled globally. This is particularly true if one wishes to conduct some Bayesian probabilistic inference. A workaround is to rather try to work hierarchically, by processing mostly independently some sub-regions (divide-and-conquer strategy), possibly taking into account global-level interaction only as region-to-region neighboring influences, or even ignoring them in first approximation as proposed in 1998 by Boyen and Koller. A first required step for this is to be able to obtain, as automatically as possible, a partition of the network in sub-regions as weakly dependant as possible one from another.

We have investigated two possible approaches for this traffic network partitioning problem. The first one is based solely on path information of floating car probe vehicles. The idea is to use the observed probe trajectories to compute some “causality measure” between links: our work is based on the hypothesis that the more often 2 road segments belong to one same vehicle path, the more traffic causality is expected between them. The first investigations were conducted some time ago, during internship at CCIT of Walid Krichene, a Mines ParisTech student now beginning his PhD at CCIT, and we formalized his results (in a draft communication submitted to forthcoming ISTTT_2013 conference) during this visiting period. A typical result on San Francisco arterial network is illustrated below.

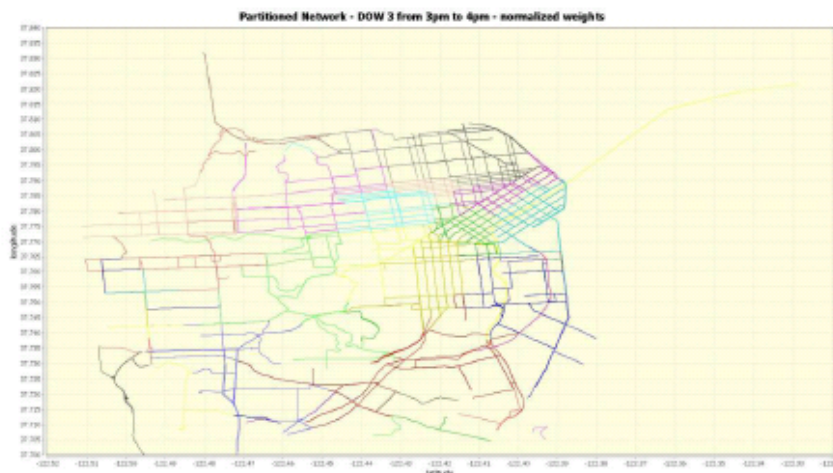


Figure 12. Example of large network partitioning obtained by processing probe vehicle trajectories on arterials inside San Francisco

The second approach for the partitioning problem is to apply, on historic of traffic data, a recently introduced data-mining algorithm called Non-negative Matrix Factorization (NMF). One of the interests of this technique is that it builds an approximation of the historic data as a superposition of a few “components”, each of which

normally correspond to highly time-correlated set of links. Experiments of this technique on CCIT estimated arterial traffic inside San Francisco had been conducted earlier by Mines ParisTech, with some results already presented in a Berkeley-Mines common communication during last TRB 2012 conference. Typical NMF components obtained on San Francisco arterial network are shown on figure 13 below.

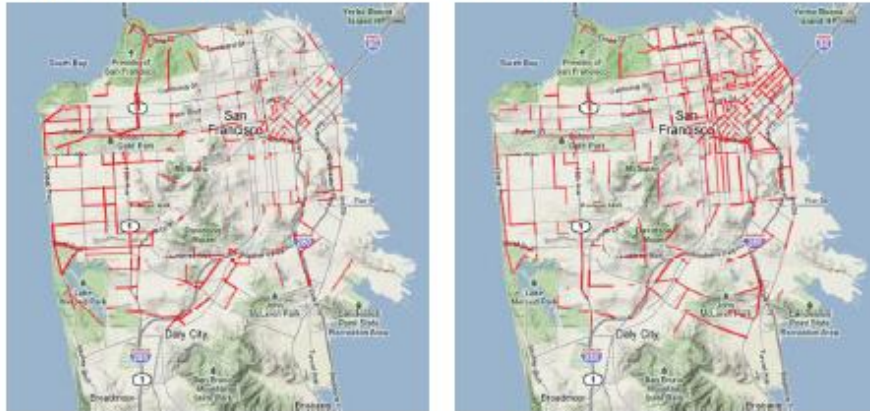


Figure 13. Examples of NMF components obtained on historic of arterial traffic inside San Francisco

During this visiting period, we formalized (in the above-mentioned draft communication submitted to ISTTT_2013) our plans for further improvement of our NMF scheme, by addition of “connected sparsity” constraints, so as to obtain more geographically-localized NMF components. This could be used for network partitioning as an alternative to, or in combination with, the probe trajectories-based partition. In particular, when the main traffic data for the network is from fixed sensors rather than floating cars (e.g. in the case of a network of freeways, such the one of the Bay Area), only the NMF-based could be used. We also defined plans for using simulated data for validation/comparison of both network partitioning approached. Illustrated below on figure 14 are some NMF components obtained on simulations of traffic in whole Paris region, on which we plan to apply also the probe trajectories based partitioning.

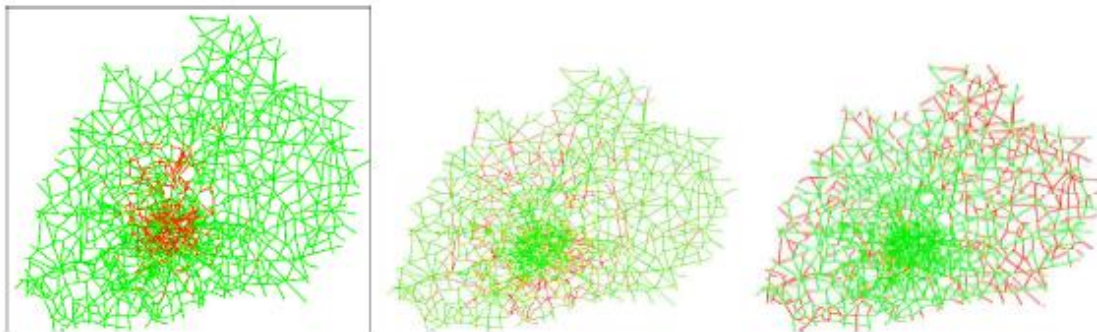


Figure 14. NMF components obtained on simulated historic of traffic for whole Paris metropolitan area; those are rather well-localized and highlight differential behavior of traffic in successive circular rings around Paris

More details on this work can be found at the end of this report, in appendix B which contains a proposition of research communication written during our visiting research period, and submitted to ISTTT13

2.2 Traffic spatio-temporal patterns analysis, and long-term forecasting

Previous research in traffic data analysis is either model-driven or data-driven. Model-driven approaches include flow physics theory and discrete physic systems, such as Cellular Automata. The complexity of urban traffic requires these models to make strong assumptions regarding data availability and/or network spatio-temporal structures and correlations. They generally require precise calibrations and are not adapted to large-scale networks. Data-driven methods are more flexible to integrate the high variability of urban traffic by extracting distinct temporal or spatial patterns from historical data. Kalman filter, neural network, probabilistic graph model, and non-linear regression, all show promising results to model fluctuations of traffic flows. However, for computations to be tractable, prior assumptions about the spatio-temporal patterns of congestion in the network are required. Typically, what is supposed is either statistical independence of individual links, which is obviously false, or dependence of each links only on their direct neighbors. To our knowledge, there is little published work that justifies these assumptions, and even less that characterizes global traffic state configurations.

Mining typical temporal dynamics of congestion over entire networks plays a key role in building a detailed model of traffic dynamics and is one of the main contributions of research work conducted at Mines ParisTech. For this purpose, we use a tensor algebra method called *Non-negative Tensor Factorization* (NTF) that extracts typical temporal evolution patterns of the global traffic state configurations from historical data and is promising for global traffic dynamics long-term and large-scale prediction. Moreover, the predicted global traffic configurations constitute prior knowledge on correlations between neighboring links or areas, which can be used to define consistency constraints for finer-grained traffic estimation and/or forecasting.

2.2.1 Non-negative Tensor Factorization (NTF) for traffic mining and forecasting

Factorization of data into lower dimensional spaces provides a compact basis to describe the data, sometimes referred to as *dimensionality reduction*. *Principle Component Analysis* (PCA) and *Non-negative Matrix Factorization* (NMF) are the most popular data factorization methods. Experimental results show that the non-negativity constraint of NMF leads to a part-based decomposition of the data and improves clustering and classifying capabilities of multivariate data when compared to PCA. NTF takes NMF a step further by adding a dimension to the 2nd order tensor factorization (matrices) while inheriting its characteristics.

The approach we propose and investigate is to use 3-way tensor $T \in \mathbb{R}^{n \times m \times l}$ to store temporal sequences of global traffic states. The indices n , m and l respectively correspond to the numbers of links, of time sampling steps in each traffic sequence (generally one day), and of traffic sequences. Each entry of the tensor $t_{i,j,k}$ represents the congestion level of link i , at time sampling step j of the traffic sequence k . Each column vector $(t_{:,j,k})$ represents the traffic state of all links at a specific time (sequence k , sampling step j) and is referred to as the *network-level traffic state*. Each frontal slice $(t_{:,:,k})$ of the tensor corresponds to the temporal variations of network-level traffic states during sequence k . In this framework, NTF is formulated as follows:

$$U, V, Q = \arg \min \left\| T - \sum_{i=1}^r (u^i \circ v^i \circ q^i) \right\|_{Fro}^2, \quad (1)$$

$$(U \geq 0, V \geq 0, Q \geq 0)$$

where u^i, v^i and q^i are the i^{th} column of the three non-negative matrices, $U \in \mathbb{R}^{n \times r}$, $V \in \mathbb{R}^{m \times r}$ and $Q \in \mathbb{R}^{l \times r}$. The operator \circ denotes the outer product between vectors. The rows in U , V and Q can be viewed as

r -dimensional *fingerprints* or *signatures* of underlying traffic spatio-temporal patterns, for each link, time sampling step and traffic sequence respectively. The notation $\| \cdot \|_{Fro}^2$ denotes the square of the *Frobenius* norm. Each frontal slice of the tensor is linearly approximated as follows:

$$T_k \approx \sum_{i=1}^r q_i^k (u^i \circ v^i), \quad (2)$$

where q_i^k is the entry located at the k^{th} column and i^{th} row of Q . The r matrices $\{u^i \circ v^i\}$, of size $n \times m$, form a linear projection basis, and the coefficients $\{q_i^k\}_{i \in \{1,2,\dots,r\}}$ represent the corresponding projection coordinates in this basis. Due to the non-negativity constraint, Eq.2 represents an **additive** superposition of that basis. Each matrix of the basis is a unit element or *part* that contributes to form the general 2D structure of the frontal slice T_k , which leads to a part-based decomposition of spatio-temporal patterns. The coordinates $\{q_i^k\}_{i \in \{1,2,\dots,r\}}$ evaluate the contributions of the basis matrices in approximating the frontal slice. Therefore, they can be considered as a r -dimensional signature of the frontal slice in the subspace spanned by the basis. In our case, these coordinates are used as a compact feature representation of large-scale traffic dynamics for the corresponding sequence. Historic traffic observations are stored in the tensor T^{historic} . Following the NTF scheme, the historic data is factorized by solving Eq. 1 as:

$$T^{\text{historic}} \approx \sum_{i=1}^r (u_{\text{historic}}^i \circ v_{\text{historic}}^i \circ q_{\text{historic}}^i) \quad (3)$$

$u_{\text{historic}}^i, v_{\text{historic}}^i$ and q_{historic}^i are the i^{th} column vector of the corresponding factorization matrices $U_{\text{historic}}, V_{\text{historic}}$ and Q_{historic} as defined in Eq.1. Hierarchical clustering on the row space of Q_{historic} indicates different temporal dynamic patterns of the network-level traffic states in the historic data.

One of our major contributions is the use of the recovered congestion dynamics pattern for long term prediction. From a *partially observed* traffic sequence M , in which the first m_1 time steps are observed, we use the learned factorization to predict the unobserved states, inferring the spatial configurations of traffic states in the network. Our reconstruction offers a trade-off between the information contained in the nearest neighbors of the observed sequence and the tensor reconstruction error and is a major contribution of this article: the projection coordinates of the K nearest neighbors of M among all frontal slices in T^{historic} are denoted $\{q_j^{NN}\}_{j \in \{1,2,\dots,K\}}$. We call $\{\bar{q}_i\}_{i \in \{1,2,\dots,r\}}$ the reconstructed coordinates of M . They are chosen as a trade-off between approximating accuracy to the partially observed ground truth (first term) and heuristic nearest neighboring information in the projected space (second term).

$$J(\bar{q}) = \left\| M - \sum_{i=1}^r \bar{q}_i (u_{\text{historic}}^i \circ v_{\text{historic}}^i) \right\|_{Fro}^2 + \lambda \sum_{j=1}^K \left\| \bar{q} - q_j^{NN} \right\|_{L2}^2 \quad (4)$$

$(\bar{q} \geq 0)$

2.2.2 Application of NTF to traffic-mining on metropolitan area

We have first tested our proposed method of large-scale simulations of the Paris metropolitan area. We simulate daylong traffic evolutions with a typical sampling rate $\sim 10\text{mn}$.

A first interesting outcome of traffic mining with NTF is to provide, in matrix V , basis vectors that correspond to regions that are highly correlated internally, and loosely coupled one with another. Typical results on simulations of Paris metropolitan area are shown on figure 15.

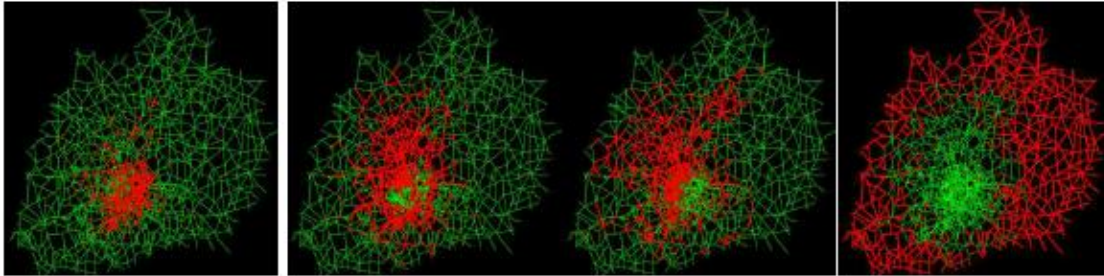


Figure 15. Illustration of NTF-extracted loosely coupled regions (each plot corresponds to a particular NTF basis vector)

Applying clustering on the NTF projections of traffic network states (i.e. all $T_{:,j,k}$, corresponding to all time steps of all simulated days) allows easy subdivision of all encountered network-level traffic states into several types of congestion patterns, as illustrated on figure 16.

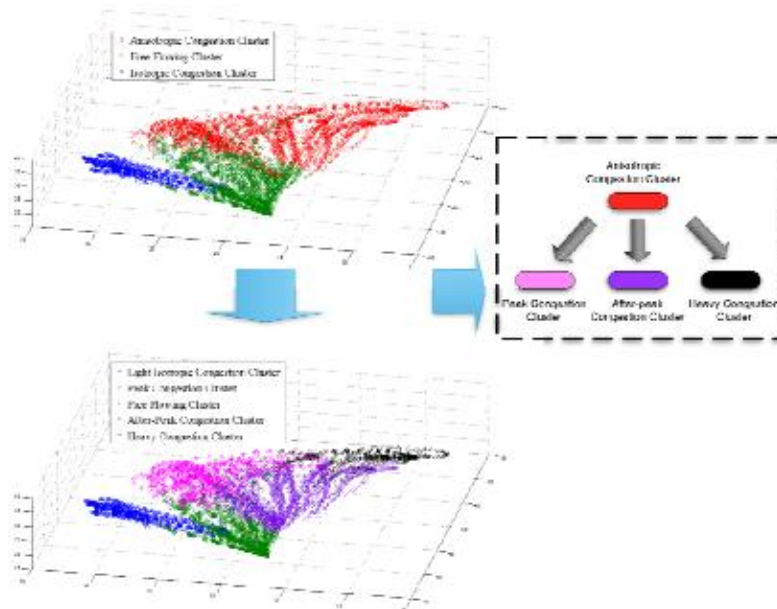


Figure 16. Clustering of network-level traffic states into types of “congestion patterns” (shown in 3D-PCA space for visualization purposes)

2.2.3 Application of NTF to traffic long-term forecasting on metropolitan area

Using the same NTF result, but clustering the traffic 1-day trajectories (rather than traffic single states), i.e. of rows of Q matrix, we can characterize different types of traffic evolutions, as shown on figure 17.

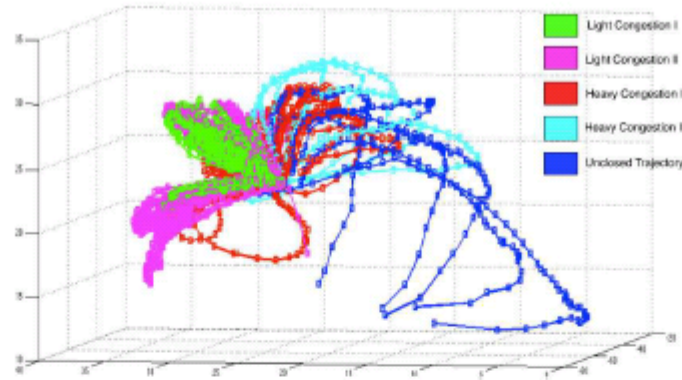


Figure 17. Clustering of the temporal evolutions of network-level traffic states into **types of “congestion dynamics”** (shown in 3D-PCA space for visualization purposes)

Using the NTF projections, any beginning of traffic evolution during a day or half-day can be mapped onto a predicted future trajectory (\bar{q} in Eq.4). Our first evaluation of this long-term and large-scale forecasting scheme shows promising results, as can be seen on figure 18.

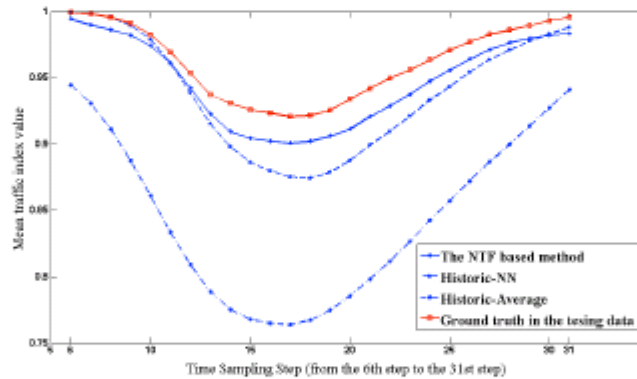


Figure 18. Long-term forecasting of network-level traffic state, by using nearest neighbors in the NTF projection space, compared to ground truth (in red), and to 2 baseline simpler techniques (dashed lines).

2.2.4 Application of NTF to extraction of spatio-temporal arterial traffic patterns

Applying the same technique to estimated arterial traffic inside San Francisco (cf. figure 13), we obtain a categorization of daily evolutions of arterial traffic in the covered area, shown on figure 19.

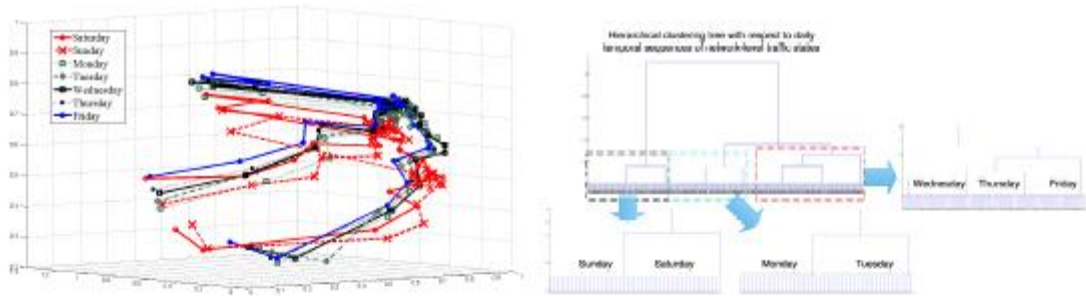


Figure 19. Clustering obtained in NTF space for the daily evolution of estimated arterial traffic inside San Francisco.

More details on this work can be found at the end of this report, in appendix C which contains a proposition of research communication written during our visiting research period, and submitted to ISTTT13

2.2.5 Application of NTF to long-term traffic forecasting for Bay Area network of freeways

When one deals with a corridor such as the Peninsula, the relevant traffic patterns are more that of freeways (including in influencing surroundings), than that of arterials. We therefore decided to begin a first feasibility test of extracting some useful space and time traffic patterns for the full Bay Area network of freeways.



Figure 20. Network of Bay Area freeways for which traffic mining of filtered PeMs data with our NTF approach is currently underway.

This work was just begun at the end of the visiting research period, and will be finalized later as part of the ongoing collaboration between Mines ParisTech and Berkeley CCIT.