Floating Car and Camera Data Fusion for Non-Parametric Route Travel Time Estimation

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Abstract—The paper proposes a non-parametric route travel time estimation method based on fusion of floating car data (FCD) and automated number plate recognition (ANPR) data. Today’s traffic management utilizes heterogeneous data collection systems which can be stationary or mobile. Each data collection system has its own advantages and disadvantages. Stationary sensors usually have less measurement noise than mobile sensors but their network coverage is limited. On the other hand, mobile sensors, commonly installed in fleet vehicles, cover relatively wider areas of the network but they suffer from low penetration rate and low sampling frequency. Traffic state estimations can benefit from fusion of data collected by various sources as they complement each other. The proposed estimation method is implemented using FCD from taxis and the ANPR data from Stockholm, Sweden. The results suggest that the fusion increases the robustness of the estimation, meaning that the fused estimates are always better than the worst of the two (FCD or ANPR), and it sometimes outperforms the two single sources.

I. INTRODUCTION

In light of increasing congestion in urban areas, monitoring and providing information about traffic conditions is critical for traffic management and effective transport policy. Travel time data may be collected from stationary automatic vehicle identification (AVI) sensors (automatic number plate recognition (ANPR) cameras, Bluetooth devices, etc.). AVI systems provide direct measurements of route travel times, but the spatial coverage is typically small and may not be representative of the network as a whole. Meanwhile, floating car data (FCD) collected from GPS devices installed in vehicle fleets or smart phones provide information from the entire network. Travel time estimation from FCD is often challenging because of low penetration rate, which means that the number of available FCD observations from vehicles traveling along the route of interest may be low if it is not a common one.

AVI and FCD have complementary strengths as FCD provides network coverage while AVI provides accurate measurements on specific route segments (larger sample size). The combination of AVI data and FCD has not been studied much in the literature, however. A data fusion methodology for estimation of freeway space-time speed diagrams based on loop detector data, AVI and FCD has been proposed [1]. For the arterial network, research on travel time estimation based on FCD has largely focused on links [2], [3]. As far as we are aware, no studies have combined stationary and mobile sensors to estimate travel time distributions on arterial network routes.

The aim of this paper is to utilize the complementary benefits of ANPR and FCD by integrating the two data sources in the estimation of arterial route travel times, where a route may be fully or partially covered by the two sources of data. The paper proposes a computationally efficient, non-parametric method for route travel time estimation using both ANPR data and low-frequency FCD. The approach estimates route travel time distributions directly from ANPR and FCD measurements partially covering the route, incorporating all information available from the data. The methodology extends ideas from kernel-based estimation [4] and is developed considering the particular features of network routes and ANPR and FCD observations. No assumptions are made regarding the form of the distribution. This flexibility is highly valuable whenever the variability of travel times is of interest, e.g., for monitoring of travel time reliability.

The paper is organized as follows: Section 2 describes the methodology, Section 3 presents a case study for Stockholm, Sweden, and Section 4 concludes the paper.

II. METHODOLOGY

A. Preliminaries

A network route is defined as an acyclic path \( \pi = (k_s, k^*, k_e) \) connecting the beginning and end links \( k_s \) and \( k_e \), and two distances \( o_s \) and \( o_e \) marking the two offsets on \( k_s \) and \( k_e \) respectively. \( k^* \) denotes 0 or more links between \( k_s \) and \( k_e \). In a special case a route can consist of only one link, i.e., \( k_s = k_e \), \( k^* = 0 \), and \( o_s < o_e \). The fraction of link \( k \) covered by the network route, denoted \( \alpha_k \), is the length of overlap between the route and the link divided by the link length. The route travel time is denoted by \( T = T(s) \) and varies stochastically between trips and as a function of the route entry time \( s \). The aim of this research is to estimate the distribution of \( T(s) \) from ANPR and FCD measurements.

a) Automatic number plate recognition (ANPR) data:

ANPR data are collected from ordered pairs of cameras which identify vehicles based on optical recognition of license numbers. An ANPR route is defined as the path between the locations of the first and the second camera (more precisely, the locations where vehicles are detected); it is assumed that there is a unique reasonable route between the two locations. A data record is created whenever the
same vehicle is identified sequentially by both cameras. A
record is a triplet \((h,s,e)\), where \(h\) is a unique ANPR route
identifier, and \(s\) and \(e\) are the timestamps of the detection of
the vehicle at the first and the second camera, respectively.

b) Floating car data (FCD): FCD consists of sequences
of reports, or probes, from vehicles traveling on the network.
Each probe is a triplet \((i,\sigma,(x,y))\), where \(i\) is a unique
vehicle identifier, \(\sigma\) is a timestamp and \((x,y)\) are the GPS
coordinates of the vehicle location at that time. In practice
the time gap between consecutive reports from the same vehicle
varies from a few seconds up to minutes. The focus in this
research is on FCD with gaps longer than a minute, usually
referred to by Low-frequency FCD. Low-frequency FCD
require preprocessing to be useful for travel time estimation.
Most importantly, reported positions must be matched to the
model of the road network and the paths taken by the vehicles
between probes must be inferred [5], [6].

B. Travel time estimation

A non-parametric method for route travel time estimation
from FCD has recently been developed [7]. The computational
efficiency allows the method to be applied on-demand
for any network route. This paper extends the method to
combine FCD with available ANPR data overlapping the
route. A common observation model, consisting of a route
and a travel time measurement, is used to represent both
ANPR data and FCD. For ANPR observations the route is
given by the fixed camera locations and the intermediate
route, and the travel time measurement \(\tau = e - s\) is obtained
from the difference between the detection timestamps.
For FCD observations the route is given by the inferred path
between two consecutive probes from the same vehicle,
and the travel time measurement \(\tau = \sigma_2 - \sigma_1\) is obtained from
the difference between the corresponding timestamps. The
framework is illustrated in Figure 1.

In general, observation \(i\) from either ANPR or FCD is
represented by a travel time \(\tau_i\), a path \(p_i = (k_{i,1},k^*,k_{i,2})\)
and two distances \(o_{i,1}\) and \(o_{i,2}\) marking the two offsets on
\(k_{i,1}\) and \(k_{i,2}\) respectively. The fraction of link \(k\) traversed
by observation \(i\) is denoted by \(\rho_{ik}\). The part of the observation
route overlapping with the network route is referred to as
the overlap route for short. The fraction of the overlap in
relation to the length of the link is denoted by \(\beta_{ik}\).

The notation used in the paper is summarized below; an
illustrative example is given in Figure 2.

| \(\tau_i\) | travel time observation \(i\) |
| \(\rho_{ik}\) | fraction of link \(k\) covered by observation \(i\) |
| \(\alpha_k\) | fraction of link \(k\) included in definition of the network route |
| \(\beta_{ik}\) | fraction of link \(k\) covered by both observation \(i\) and network route |
| \(\ell_k\) | length of link \(k\) |
| \(t_{k,0}^i\) | prior travel time of link \(k\) |

ANPR and FCD observations are processed together in
three steps: transformation, weighting, and aggregation.

1) Transformation: Each observation partially covering
the network route is transformed into an observation of
the actual route travel time. The step consists of four sub-
parts: concatenation, allocation, scaling, and route entry time
estimation. Concatenation applies to FCD and sequences of
ANPR cameras, where a vehicle may generate multiple data
records along the route. It is reasonable, however, to consider
one passage of a vehicle on the route as one travel time
observation. Consecutive observations from the same vehicle
are thus concatenated into a single travel time observation.

For each observation \(i\), the observed travel time \(\tau_i\) is
then allocated between the network route and the adjacent
network. The allocation is based on prior knowledge of link
travel times \(t_{k,0}^i\) and the distance traversed on each link. Prior
link travel times can be estimated using historical data and
be categorized based on time of day, day of week, season,
weather condition, etc. and become updated on a rolling
horizon manner so that estimated link travel times of previous
time interval have impact on allocation of the observations
in the next time interval. In cases prior link travel times are
unavailable or cannot be estimated, free-flow travel times
can be used. In general, the assumption here is that the
fraction of time spent on the overlap route in relation to
the whole FCD route, \(\phi_i\), is the same as for the prior travel
times on the same sections. The travel time allocated to the
network route is then \(\tau_i = \phi_i \tau_{i,s}\), where the allocation factor
\(\phi_i\) is \(\phi_i = \sum_k \beta_{ik} t_{k,0}^i / \sum_k \rho_{ik} t_{k,0}^i\). The allocation factor
is 1 for observations traversing only the network route and
approaches 0 as the distance traversed on adjacent links
increases.

The travel time observations are then scaled up to the en-
tire network route. Similar to the allocation, the assumption
is that the ratio between the travel time on the overlap route
and on the network route is the same as for the prior travel
time estimates on the same sections. The scaled route travel
The time that each observed vehicle passes the beginning of the network route is the basis for grouping observations to time intervals and aggregating, but is in general not observed. For each observation the route entry time $s'$, real or hypothetical, is estimated based on the prior travel times along the same lines as the allocation and the scaling.

2) Weighting: Each observation $T_i$ is assigned a weight $\omega_i$ that determines its influence in the estimation of route travel time statistics. Observations are weighted for three distinct reasons: to reflect the representativeness in relation to the network route; to correct for sampling bias due to uneven route coverage; and to reflect the relative reliability of FCD and ANPR measurements. The final weight is the product of the representativeness weight $\nu_i$, the sampling bias weight $\lambda_i$ and the source reliability weight $\gamma_i$, i.e., $\omega_i = \nu_i \lambda_i \gamma_i$. In this paper $\gamma_i$ is set to 1 for both ANPR and FCD observations.

Less overlap with the network route means that the representativeness as a network route observation is lower and that the potential for error in allocation and scaling is higher. Observations are thus weighted based on the allocation and scaling factors, $\nu_i = \theta_1^{1/\theta_2} \eta_i^{1/\theta_2}$. The parameters $\theta_1$ and $\theta_2$ control how fast the weight function decays as the overlap with the adjacent networks increases, and the overlap with the network route decreases, respectively.

Route coverage is evaluated at the link level. Let $N_k$ be the number of observations covering (partially or fully) link $k$, or $N_k = \sum_i \lfloor \beta_{ik} \rfloor$. The weight $\lambda_i$ is then the inverse of the weighted average coverage for the traversed part of the route, i.e., $\lambda_i = \sum_k \beta_{ik} t_k^0 / \sum_k \beta_{ik} t_k^0 N_k$.

3) Aggregation: Statistics of the route travel time distribution are calculated from the observations $T_i$ and the associated weights $\omega_i$. The statistics are aggregated based on the route entry time of each observation. For example, the mean route travel time estimator is $\hat{\mu}_T = \sum_i \omega_i T_i / \sum_i \omega_i$. Other statistics of the travel time distribution such as variance and percentiles are also straightforward to calculate [7].

III. APPLICATION

The proposed travel time estimation method is applied on two routes in the arterial network of Stockholm, Sweden. FCD are collected by a GPS-based taxi fleet management system covering about 1500 taxis. Each taxi broadcasts its location, timestamp, id number, and status (free/hired) once every two minutes on average [8]. A map-matching and path inference algorithm [6] is performed on the raw FCD. The ANPR system in Stockholm measures direct travel time of many major routes. ANPR data typically have significant amounts of noise and need to be filtered before travel time statistics are calculated. The method introduced by Kazagli et al. [9] is used for ANPR filtering.

For both FCD and ANPR, data from Mondays through Thursdays between 6 a.m. and 10 p.m. are used. Data were collected from September 15, 2012 to September 15, 2013. After path inference, only observations with hired status are utilized for travel time estimation. The prior link travel times $t_k^0$ for the network were estimated from FCD by applying the proposed method on each individual link (i.e. similar to the way $\hat{\mu}_T$ is calculated but at the link level). The allocation, scaling and weighting of FCD in this step (estimation of prior link travel times) are performed based on the length and free-flow speed (posted speed limit) of each link. The reason that FCD is used for prior link travel time estimation is that it has a greater spatial coverage compared to ANPR data which covers a limited number of links. In general, however, the fusion methodology proposed here can be used also for the prior link travel times.

Parameters $\gamma_i, \theta_1$ and $\theta_2$ are set to 1 in this paper. If ground-truth travel time data were available, they can be selected using cross-validation techniques.

A. Experimental setup

Two network routes are defined for the experiment, denoted as routes 111 and 112 in Figure 3. Route 111 (112) starts from the beginning of ANPR route 51 (52) and ends at the end of ANPR route 34 (54). The network routes are intentionally defined as the combination of two consecutive ANPR routes for evaluation purposes. Since consecutive ANPR routes $r_1$ and $r_2$ share the same camera at their connection point, direct travel time observations for the combined route $R$ can be calculated by matching the exit timestamp of $r_1$ with the entry timestamp of $r_2$. In other words, travel times of routes 111 and 112 are not reported by the ANPR system, but calculated afterward by matching ANPR timestamps and summing up the travel times of corresponding sub-routes. The travel times of the matched ANPR observations are used as references for evaluating the estimated travel time using different combinations of data sources.

The mean and the 25th, 50th (median) and 75th percentiles of the travel time distribution of route $R$ is estimated using FCD and ANPR data considering the following scenarios:
i) Only FCD that fully or partially overlap the route $R$
ii) Only ANPR of $r_1$
iii) Only ANPR of $r_2$
iv) ANPR of $r_1$ and FCD
v) ANPR of $r_2$ and FCD

Travel time observations are grouped by route entry time-stamp into 15-minute intervals, and the travel time statistics are calculated for each time interval ($N = 64$ intervals from 6 a.m. to 10 p.m.). The similarity between the estimated travel time statistic and the reference is evaluated using the root-mean-square error (RMSE) across all time intervals.

B. Results

Figure 4 shows the estimated travel time of the two routes, 111 and 112, under the data availability scenarios mentioned above. In general, the estimation method captures the trend across the day reasonably well in all scenarios, in particular for the mean and median travel time.

The RMSE relative to the matched ANPR measurements, as well as the number of observations available for the estimation, are shown in Tables I and II. It can be seen that “only FCD” performs better than “only ANPR” in some cases but worse in others, and the results of “only ANPR” differ significantly depending on which ANPR route is used. The estimator fusing ANPR and FCD is always better than the worst of “only ANPR” and “only FCD”, and in some cases is better than the best of the two. The results suggest that the fusion of ANPR and FCD increases the robustness of the estimation.

A network route may have multiple sections with different traffic characteristics. Because of such biases, extrapolating the travel times of a section may or may not result in good estimates of the total travel time of the entire route depending on how similar the selected sub-route is to the entire route. In the two examples, the sub-routes covered by ANPR are not similar in terms of traffic characteristics, meaning that one of them is better in estimating the travel time of the combined route than the other one. The RMSE errors imply that the estimates using only FCD (scenario i) are in between the estimates based on the two ANPR sub-routes either separately or combined with FCD (i.e., between scenarios (ii, iv) and scenarios (iii, v)). Thus, if the ANPR data cover the sub-route with characteristics most dissimilar to the full route, then fusion with FCD improves the estimates. On the other hand, fusion of FCD with an ANPR sub-route that is similar to the full route results, in most cases, in only slight changes in the estimates.

In general, some reasons for the differences between the estimated travel times in the various scenarios are as follows:

- ANPR observations come from the entire population of vehicles while the FCD are generated by taxis. Taxis may not be a representative of the entire population in terms of driving behavior, route choice, etc., which results in different reported travel times. Some of these biases can be corrected for as demonstrated in [7].
- The filtering method used for ANPR may classify some of the longer observations as outliers and exclude them, resulting in a distribution with shorter right tail.
- The method of pairing ANPR observations of two consecutive routes may introduce errors where there is more than one matching timestamp.
- Map matching and path inference of sparse FCD are other sources of error. Errors in path inference result in wrong assignment of travel time to network links.

IV. Conclusion

The paper proposes a non-parametric route travel time estimation method based on fusion of FCD and ANPR data. The approach combines the network coverage of FCD with the accurate measurements on specific route segments of ANPR. A common observation model for both sources of data is used to estimate travel time through a sequence of transformation, weighting and aggregation. Application results suggest that the fusion increases the robustness of the estimation, meaning that the fused estimate is always better than the worst of the two (FCD or ANPR), and sometimes better than the best of them. Further research is needed to evaluate the method on a varied set of network routes and data sources, and to calibrate the parameters of the method to optimize the performance.

REFERENCES

Fig. 4: Comparison of estimated mean and percentiles of the travel time of routes 111 and 112 by various data availability scenarios against direct ANPR observations.
TABLE I: Error of estimated travel time of route 111 by various scenarios against the "Only ANPR" scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Only FCD</th>
<th>Only ANPR$_{51}$</th>
<th>Only ANPR$_{34}$</th>
<th>Fusion of ANPR$_{51}$ and FCD</th>
<th>Fusion of ANPR$_{34}$ and FCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>0.28</td>
<td>0.46</td>
<td>0.26</td>
<td>0.34</td>
<td>0.23</td>
</tr>
<tr>
<td>25$^{th}$ percentile</td>
<td>0.84</td>
<td>0.72</td>
<td>0.73</td>
<td>0.74</td>
<td>0.77</td>
</tr>
<tr>
<td>50$^{th}$ percentile</td>
<td>0.49</td>
<td>0.50</td>
<td>0.33</td>
<td>0.46</td>
<td>0.34</td>
</tr>
<tr>
<td>75$^{th}$ percentile</td>
<td>0.26</td>
<td>0.29</td>
<td>0.53</td>
<td>0.22</td>
<td>0.45</td>
</tr>
<tr>
<td>Total number of observations</td>
<td>84,590</td>
<td>103,427</td>
<td>1,001,696</td>
<td>188,013</td>
<td>1,086,286</td>
</tr>
</tbody>
</table>

TABLE II: Error of estimated travel time of route 112 by various scenarios against the "Only ANPR" scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Only FCD</th>
<th>Only ANPR$_{52}$</th>
<th>Only ANPR$_{54}$</th>
<th>Fusion of ANPR$_{52}$ and FCD</th>
<th>Fusion of ANPR$_{54}$ and FCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>0.30</td>
<td>0.16</td>
<td>0.53</td>
<td>0.16</td>
<td>0.44</td>
</tr>
<tr>
<td>25$^{th}$ percentile</td>
<td>0.33</td>
<td>0.22</td>
<td>0.68</td>
<td>0.23</td>
<td>0.60</td>
</tr>
<tr>
<td>50$^{th}$ percentile</td>
<td>0.18</td>
<td>0.16</td>
<td>0.28</td>
<td>0.14</td>
<td>0.19</td>
</tr>
<tr>
<td>75$^{th}$ percentile</td>
<td>0.37</td>
<td>0.25</td>
<td>0.89</td>
<td>0.25</td>
<td>0.71</td>
</tr>
<tr>
<td>Total number of observations</td>
<td>95,944</td>
<td>305,227</td>
<td>768,577</td>
<td>401,171</td>
<td>864,521</td>
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