An Improved Travel-time Estimation Algorithm using Dual Loop Detectors

J.W.C. van Lint

H.vanLint@citg.tudelft.nl
Transportation Planning and Traffic Engineering Department
Faculty of Civil Engineering and Geosciences
Delft University of Technology
Stevinweg 1, P.O. Box 5048, 2600 GA Delft
(t) +31 15 2785061, (f) +31 15 2783179

N.J. van der Zijpp

zijpp@modelit.nl
Modelit
Rotterdamse Rijweg 126
3042 AS Rotterdam
The Netherlands
(t) +31 10 4623621, (f) +31 10 4623637

ABSTRACT

This paper presents an algorithm for the off-line estimation of route-level travel times for uninterrupted traffic flow facilities, such as motorway corridors, based on time-series of traffic speed observations taken from the sections that constitute a route. The proposed method is an extension of an existing and widely used method known as the trajectory method. The novelty of the new method is the fact that trajectories are constructed based on the assumption of piecewise linear (and continuous at section boundaries) vehicle speeds rather than piecewise constant (and discontinuous at section boundaries) speeds.

Based on these assumptions, mathematical expressions are derived that describe the trajectories within each section. These expressions can be used to replace their existing counterparts in the traditional trajectory methods.

A comparison of the accuracy of the new method and the existing method has been carried out based on simulated data. This comparison shows that the RMSE value for the new method is about half the RMSE value for the existing method. After decomposing this RMSE error in a bias and a residual error, it turns out that the existing method significantly overestimates the travel time. However the largest part of the reduction of the RMSE value is still due to a reduction of the residual error. In other words: also if both methods are corrected for their bias the new method performs significantly better.

Keywords: Trajectory method, Travel Time Estimation, Vehicle Trajectories, Offline traffic analysis

Document properties: words:5760; figs:7; tables:1;

LIST OF SYMBOLS

i	denotes a vehicle
p, P	measurement period and total number of measurement periods respectively
t_0, t_1	start / end measurement period p
k, K	section and total number of adjacent sections comprising a route
x_0, x_1	start / end location of section k
x_d, x_{d+1}	location of detectors d and $d+1$
L_k	length of section k
$\{x^0_{ikp}, t^0_{ikp}\}$	entry location and time of a vehicle i in section k, period p
$\{x^*_{ikp}, t^*_{ikp}\}$	exit location and time of a vehicle i in section k, period p
$v(x,t)$	the 'true' speed function over space and time

$x_i(t)$	trajectory of vehicle i as function of time
$v_i(t)$	speed of vehicle i as function of time
$V(k,p)$	mean speed on section k during time period p
$V_{TMS}(d,p)$	arithmetic time mean speed at location d during time period p
σ^2_{TMS}	standard deviation of speeds at location d during time period p
$V_{HMS}(d,p)$	harmonic time mean speed at location d during time period p
$V_{SMS}(k,p)$	space mean speed on section k during time period p
r	headway between vehicles (resolution of trajectory method)
$TT_k(t_0)$	section level travel time on section k for vehicles starting at time instant t_0
$TT_k(p)$	section level travel time on section k during measurement period p
PCSB (…)	Piece-wise Constant Speed-Based (trajectory method)
PLSB (…)	Piece-wise Linear Speed-Based (trajectory method)

INTRODUCTION

This paper presents an improved algorithm for the off-line estimation of route-level travel times for uninterrupted traffic flow facilities, such as motorway corridors, based on time-series of traffic speed observations.

Off-line travel time estimation algorithms are typically used to gather statistics on the performance of transport systems. These statistics can be used to evaluate performance indicators that express policy objectives, or in studies that evaluate the impact of new traffic measures, especially if these contain a before and after study *(1)*. Travel time estimates are required as well in systems that analyze other aspects of the traffic system, such as estimators of dynamic Origin-Matrices, such as DelftOD *(2)*. Finally, they can be used as a (tracking) component in more complex traffic control and traveler information systems *(3)* or as a means to compile historic databases that support trend analysis and conditional predictions of travel time *(4)*.

The paper studies a class of travel time estimators that will be referred to as *trajectory methods*. Travel time estimators of this class have in common that travel time estimates are derived from imaginary vehicle trajectories that are constructed based on observed speeds or estimated section level travel times. Many travel time estimators that are used in practice can be viewed as a member of this class.

The simplest example of a trajectory method arises if the section level travel times are assumed to equal the travel times that are derived from the observed speeds *at time of departure*. In this case an estimate results that is known as the *instantaneous* travel time. Because instantaneous travel time estimates can be derived on-line they are sometimes used as a predictor of travel time. Obviously a more accurate estimator results if section level travel times are assumed to depend on the speeds at time *of entering the section*. To make sure the FIFO property applies to the constructed artificial trajectories, this assumption should be further refined by recognizing that prevailing speeds may change while traversing the section. In this case trajectories are built assuming piecewise constant speeds. Given a starting position and departure time, each next point of the trajectory is constructed by either computing the time instant that the trajectory enters the next section of the path or the longitudinal position on the current section that is reached when the next speed observation becomes available, whatever comes first.

Attractive properties of this method, which we will refer to as the '*Piecewise Constant Speed Based*' (PCSB) trajectory method, are the ease of implementation, its conceptual simplicity, and its accuracy *(5)*, *(6)*. These properties have led to many practical applications of the method, see amongst others *(1)*, *(2)*, and *(11)*. As a limitation of the trajectory method the requirement of a quite dense spacing of speed detectors (typically 500 meters) should be noted.

In the present paper we propose a modification to the PCSB trajectory method in which we replace the assumption of *piecewise constant* speeds with the assumption of *piecewise linear* speeds: The speed in between two detection points on a path is modeled by the convex combination of the speeds observed at the upstream and downstream detector. It turns out that based on these assumptions, elegant mathematical expressions can be derived that describe the trajectories in between the two detectors. These equations can be used to directly replace the linear equations in the traditional trajectory method. Later sections in this paper point out in detail how existing PCSB-trajectory methods can be adapted to reflect these new insights with little effort. We will refer to the new method as the '*Piecewise Linear Speed Based*' (PLSB) trajectory method.

It is hypothesized that this simple modification leads to a considerable improvement of accuracy because an approximation based on piecewise linear functions enables a better representation of the 'true' time and space dependent speed function $v(x,t)$ than an approximation that is based on piecewise constant functions. If this improved accuracy can indeed be achieved it may, if one prefers, be traded in for wider detector spacing and hence yield considerable cost-savings for road-authorities.

The remainder of the paper starts with a brief overview of travel time estimation procedures that are based on roadside detectors, and subsequently focuses on the class of trajectory methods. We first elaborate on how to estimate section level travel times with constant speeds and speed as a convex combination of up- and downstream speeds respectively. These section level travel time estimators are the building blocks of both trajectory methods mentioned above, which is subsequently discussed in detail. The paper is concluded with a series of numerical tests. Because of the lack of practical datasets that feature both accurate speed observations and direct observations of travel time, the experiments are based on data that are generated using a microscopic traffic flow simulator.

TRAVEL TIME ESTIMATION FROM ROAD SIDE BASED DETECTORS: A SHORT OVERVIEW

Given a set of road-side detectors, there are a number of ways to estimate travel times. In this discussion we will confine ourselves to detectors that observed traffic flows and speeds, such as (double) loop detectors. If the speed measurements are accurate, the detector spacing small, and the observed speeds are aggregated over short periods, then travel times can more or less directly be observed using a trajectory method that is based on these speed measurements. These will be discussed in detail in later sections. Otherwise, additional information should be derived from the flow measurements, if available, or by applying a traffic flow model.

The traffic flow measurements may be used in two ways. The first way is the upstream and downstream recognition of platoons. This method depends on platoons propagating undisturbed through a corridor. A platoon consists of a group of vehicles driving close together. The behavioral mechanism that is responsible for the forming of platoons also keeps them together for several kilometers. At a detection point, a platoon is observed as a peak in the time series of observed traffic flows. The method of estimating travel time by tracking platoons is dependent on the presence of platoons and therefore generates a number of isolated travel time observations rather then a continuous stream of observations. Moreover, no observations will be available if traffic is congested or if traffic volumes are low (in the latter case one may assume free flow travel time). The second way in which time series of traffic flow observations can be used to estimate travel times is to apply the conservation of flow property. Provided that each vehicle that is observed at an upstream detector is due to be observed downstream, and FIFO applies, the travel time of the n^{th} vehicle that crosses the upstream detector equals the delay with which the cumulative vehicle count at the downstream detector reaches n. In other words if $Q_1(t)$ and $Q_2(t)$ denote the cumulative upstream and downstream vehicle count respectively, the travel time for vehicles departing at time t equals $Q_2^{-1}[Q_1(t)]-t$. If FIFO does not apply the latter formula still represents the mean travel time. Probably a greater practical value of this method is in monitoring *changes* in the travel time, rather then in monitoring its absolute level. This is because detection errors accumulate in the cumulative traffic counts. In their performance, the platoon recognition method and the conservation of flow based method complement each other quite effectively. Their combined behavior has been studied in at least one occasion *(7)*.

If the available data support none of the above described methods it becomes necessary to rely more heavily on modeling assumptions. For example the fundamental diagram describes a relation between flow and speed that may be exploited to make rough estimates of section level travel times if only aggregate observations of flow are available. At a more detailed level one may formulate and solve a set of differential equations based on a macroscopic flow model. If this flow model is of the Lighthill-Whitham-Richards class of models *(8)*, meaning that expected velocity can be described as a function of the local density, it suffices to compute the propagation of the shockwaves. A recent contribution *(9)* uses a triangular fundamental diagram (speed-flow relationship) as an alternative to generalizing local speeds to an entire section. In this context the approach presented in that paper also fits in the class of trajectory methods.

Finally, at an even more abstract level one may apply classical assignment models. These models not only apply aggregate relationships between flow and travel time, but also exploit the equilibrium properties of the traffic system, by requiring that the travel times on different (used) routes are in equilibrium.

The value of the different techniques mentioned above is in the fact that they can be applied independent from each other to a great extent. By combining different, independent methods, the end result becomes more accurate and robust. As mentioned in the introduction, this paper will concentrate on the class of trajectory methods. The next sections first present speed-based section level travel time estimation, which is the fundamental building block of the trajectory method. Next, we present the general framework of the trajectory method, and show how both methods piece-wise constant and piecewise linear speeds can be implemented.

SPEED-BASED SECTION LEVEL TRAVEL TIME ESTIMATION

Speed-based section level travel time estimation is the basic component of the trajectory method. The experienced travel time on section k ranging over $[x_0, x_1]$ is defined as the time needed for a vehicle i to traverse that particular section (Figure 1). The speed $v(x,t)$ of such an imaginary vehicle at a particular point $\{x,t\}$ depicts the *steepness* of its trajectory . In practice, we have no knowledge of the 'true' $v(x,t)$, other then the observed speeds at fixed locations averaged over fixed intervals. The two methods we will describe in the next sections differ primarily in how they generalize these local time averaged measured speeds to the remainder of the road section.

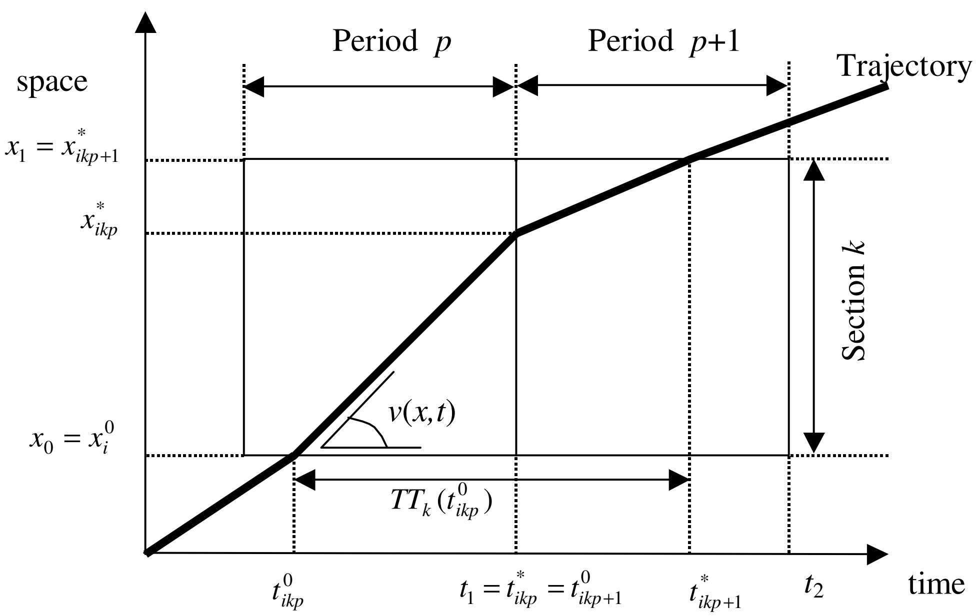


Figure 1: Example trajectory through space-time cells $\{k, p\}$ and $\{k, p+1\}$. All speed-based travel-time estimation techniques aim to reconstruct *imaginary* vehicle trajectories by generalizing local measured speeds (e.g. at loopdetectors) over space, and hence calculate travel time. In the figure above speeds are conceived constant over each cell $\{k, p\}$.

Section Level Travel Time Estimators Based On Constant Speeds

The trajectory of an individual vehicle i driving at section k during period p at constant speed $V(k,p)$ is described by:

$$x_i(t) = V(k,p).(t - t^0_{ikp}) + x^0_{ikp} \tag{1}$$

where (x^0_{ikp}, t^0_{ikp}) is the initial point of vehicle i's trajectory in the cell $\{k, p\}$. This equation allows one to compute at what time the end of the section is reached or which position is reached at the end of period

p, whatever comes first (we refer to equation (7) for the exact formula). We denote this point by (x^*_{ikp}, t^*_{ikp}). As such, equation (1) forms a basic building block of what we will refer to as the Piecewise Constant Speed Based (PCSB) trajectory method.

If we want to obtain unbiased estimates of travel time using the PCSB trajectory method, we need to be aware of the fact that the speed of individual vehicles may fluctuate and that different drivers maintain different speeds. Most speed detection systems record time-mean speeds at fixed locations, averaged over fixed time intervals (and hence multiple vehicles). These recorded speeds are not necessarily the ones that one would like to substitute in (1) when one aims at computing the mean travel time over a larger group of vehicles.

In *(5)*, *(6)*, *(11)*, *(12),* the speed that is substituted in (1) is given by:

$$V(k,p) = 2.\left(\frac{1}{V_{TMS}(d,p)} + \frac{1}{V_{TMS}(d+1,p)}\right)^{-1} \tag{2}$$

in which section k is considered enclosed between detectors d and $d+1$, and $V_{TMS}(d,p)$ equals the time mean speed observed at detector d during period k. Substituting this value is equivalent to assuming that each vehicle maintains speed $V_{TMS}(d,p)$ up to the middle of the section and maintains speed $V_{TMS}(d,p)$ for the other half of the section. The approach described in *(15)* substitutes the minimum of $V_{TMS}(d,p)$ and $V_{TMS}(d+1,p)$ instead.

As demonstrated in for example *(10)*, the assumption of stationarity and homogeneity (which yields that arithmetic time mean and space mean speed are equal) causes a significant bias, deteriorating travel time estimation performance. Leutzbach *(17)* shows that under stationary conditions the local harmonic time mean (V_{HMS}) equals the desired space-mean speed, which would remedy this bias. But reprogramming local detection devices to calculate V_{HMS} instead of V_{TMS} may well be a very costly and impractical operation. Fortunately, provided that we collect local speed variances (or may be able to estimate them), there also exists an analytical relationship[1] between the local arithmetic time mean speed and space mean speed, which is used in *(9)* to correct for this bias:

$$V^*_{SMS} = \frac{V_{TMS} + \sqrt{V^2_{TMS} - 4\sigma^2_{TMS}}}{2} \text{ with } \sigma^2_{TMS} < \frac{1}{4}V^2_{TMS} \tag{3}$$

Where σ^2_{TMS} denotes the estimated or observed speed variance. Clearly, the arithmetic time mean speed will always be equal or larger then the space mean speed. Usage of the arithmetic mean hence leads to underestimating travel times.

A last issue that is worth mentioning in this context, is that not all speed detection systems based on inductive loops are accurate over the full applicable speed range. Especially at low vehicle speeds and stop an go traffic it is not always possible to get accurate and representative read outs of mean vehicle speeds from these detectors. In these cases better results are obtained if speeds are extrapolated based on observed flows using a speed-flow relationship, see (*10*). The same applies if the speed and speed variance cause approximation (6) to be out of its applicable range, notably if $\sigma_{TMS} > \frac{1}{2}V_{TMS}$

In sum, section level travel times can be estimated fairly accurately using the assumption of constant speeds, given that we use (or at least approximate) the harmonic time mean speed at detector locations instead of the arithmetic time mean. Calculating section travel time with the latter leads to a significant bias (an underestimation), especially when speed variances are high, which is for instance the case when congestion sets in or dissolves. Unfortunately, just in those situations accurate travel time estimates are most valuable.

---

[1] Equation (3) holds exactly if speed probability density functions in both space (section) and time (location) are symmetrical; otherwise it must be considered an approximation

Section Level Travel Time Estimators Based On a Linear function of Speed

When the travel time estimators presented in the previous section are used at path-level they result in piece-wise linear trajectories. Vehicles are thought to instantaneously change their driving speed once entered a new section. In reality, this transition will occur in a more smoothed fashion: vehicles are likely to anticipate to slower or faster speed regimes downstream and gradually adapt their speeds to it. We propose to relax the notion of constant speeds, and consider the speed $v_i(t)$ of a vehicle i traversing a section between detector locations d and $d+1$ as a function of the distance of that vehicle to these up- and downstream detectors at x_d and x_{d+1} we obtain:

$$v_i(t) = V(d,p) + \frac{x_i(t) - x_d}{x_{d+1} - x_d}\left(V(d+1,p) - V(d,p)\right) \tag{4}$$

Let x^0_{ikp} again denote the entry location of a vehicle i in section k $[x_d, x_{d+1}]$ at entry time t^0_{ikp} such that

$$x_i(t^0_{ikp}) = \begin{cases} x^0_{ikp}, & t^0_{ikp} = t_0 \\ x_0, & t^0_i > t_0 \end{cases} \tag{5}$$

where

$$x_d \le x_i(t) \le x_{d+1}$$

Note that speed in (4) is in fact a convex combination of local speeds, implying that we still generalize local speeds over space, and hence that we still need to correct for space-mean speed to avoid the bias mentioned in the previous section. Equation (4) is an ordinary differential equation, for which the solution reads:

$$\begin{aligned} x_i(t) &= x^0_{ikp} + \left(\frac{V(d,p)}{A} + x^0_{ikp} - x_d\right)\cdot\left(e^{A\cdot(t - t^0_{ikp})} - 1\right) \\ A &= \frac{V(d+1,p) - V(d,p)}{x_{d+1} - x_d} \end{aligned}, \tag{6}$$

given constraints (5). In the limit that $A \to 0$ (i.e. $V(d,p) = V(d+1,p)$), expression (6) reduces to equation (1), which is the trajectory of a vehicle traveling at constant speed $V(k,p)=V(d,p)$. Equations (4) to (6) are the basic building blocks of what we will refer to as the Piecewise Linear Speed Based (PLSB) trajectory method.

PATH LEVEL TRAVEL TIME ESTIMATION WITH THE TRAJECTORY METHOD

General Framework of the Trajectory Method

In the introduction we roughly outlined the trajectory method; in this section we will present it in detail. The objective of the trajectory method is to estimate travel times along a path of adjacent sections by means of reconstructing *imaginary vehicle* trajectories. Let us assume that each section has detectors measuring vehicle speeds at the up-and downstream edge respectively. Let us also assume that these detectors produce harmonic time averaged speeds[2] for each measurement period p. Finally, let us define our path consisting of K adjacent sections, for which we have detector measurements

---

[2] see previous section

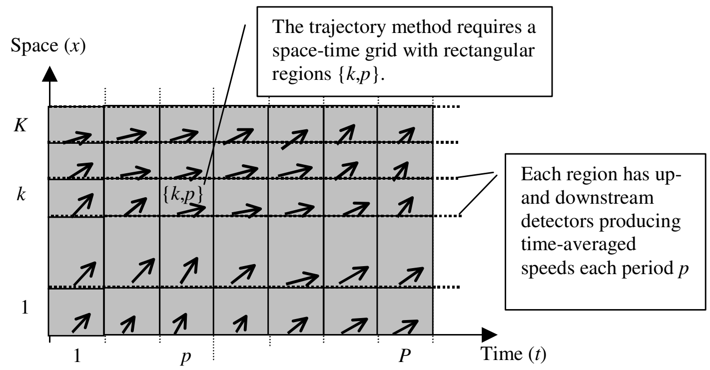


Figure 2: Trajectory methods require a space-time grid of regions $\{k,p\}$, which are enclosed between up- and downstream detectors and have (duration) length p.

In an off-line situation the data provided by these detectors comprise a space time grid of regions $\{k,p\}$, $k\in[1, \ldots, K]$, and $p\in[1, \ldots, P]$, see Figure 2. As noted before, in this space-time grid, we only know prevailing local speeds of the detectors at the up- and downstream edges of each region for each measurement period p. Now let us suppose *imaginary* vehicles traverse this grid, starting at section 1 (x=0) each r time-steps.

The headway r between consecutive vehicles at the starting points is usually referred to as the *resolution* of the trajectory method. For ease of notation let us define each region $\{k,p\}$ as a rectangular area in space-time with bottom left corner $\{x_0,t_0\}$ and top-right corner $\{x_1,t_1\}$. The trajectory algorithm for a single vehicle trajectory can now be schematically presented as follows:

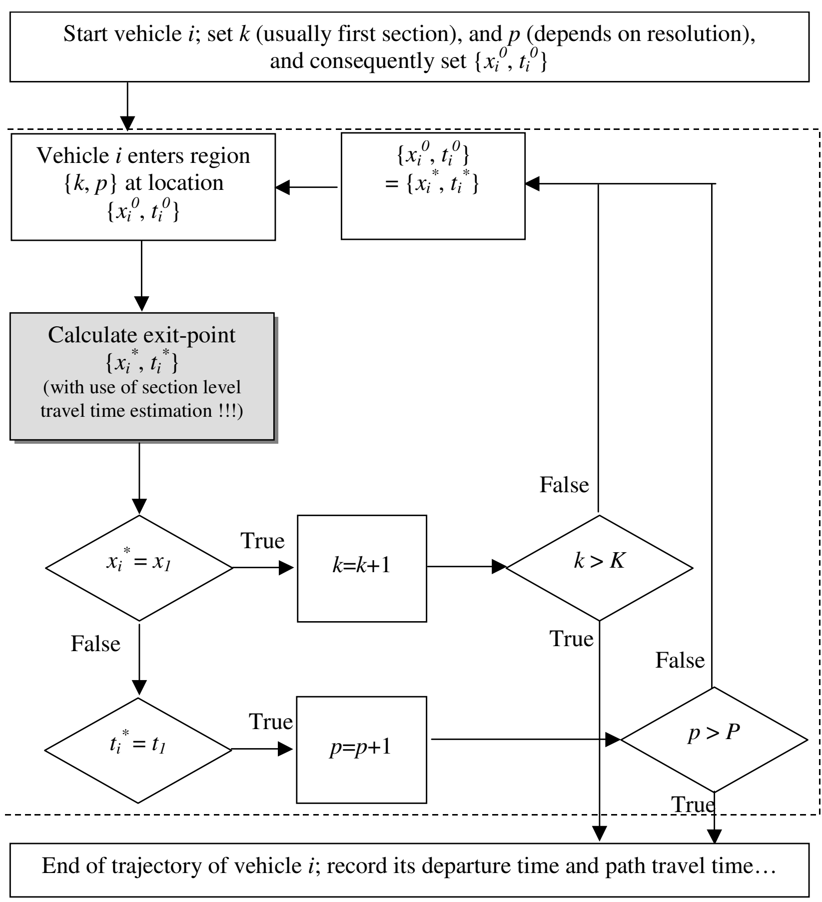


Figure 3: schematic representation of a trajectory method; different section level travel time estimators can be plugged in the framework easily (grey box left center in the schema).

Clearly, all we require to add points to the individual trajectories is the location in space time where they *exit* their current region $\{k,p\}$, which is emphasized by the grey box in Figure 3. This exit-point determines in turn the entry-point of the vehicle in the next region, and allows us to deduce path-level vehicle trajectories, and hence path travel times. The grey box (left center) in Figure 3, is the only part of the algorithm that we need to adapt to apply piece-wise linear, instead of piece-wise constant speeds.

Trajectory method based on Piece-Wise Constant Speeds

Based on the findings in "Section Level Travel Time Estimators Based On Constant Speeds", the exit location x^*_{ikp} and exit time t^*_{ikp} of vehicle i can now be calculated as follows:

$$\{x^*_{ikp}, t^*_{ikp}\} = \begin{cases} \left\{x_1, \dfrac{(x_1 - x^0_{ikp})}{V(k,p)} + t^0_{ikp}\right\}, & V(k,p)\cdot(t_1 - t^0_{ikp}) + x^0_{ikp} > x_1 \\ \{V(k,p)\cdot(t_1 - t^0_{ikp}) + x^0_{ikp}, t_1\}, & \textit{otherwise} \end{cases} \tag{7}$$

Equation (7) simply states that a vehicle i exits region $\{k, p\}$ either on the vertical edge where $t=t_1$ or on the horizontal edge where $x=x_1$. Note that $V(k,p)$ is considered the constant speed on section k, and is calculated in our case with equation (3).

Trajectory method based on Piece-Wise Linear Speeds

Based on the findings in "Section Level Travel Time Estimators Based On a Linear function of Speed", the exit location x^*_{ikp} and exit time t^*_{ikp} of vehicle i can be calculated in a similar fashion as in equation (7). Recall that we consider the speed on section k a convex combination of the time average speeds at up- and downstream detectors, denoted by $V(d,p)$ and $V(d+1,p)$ respectively. Again we have applied (3) on the local speeds. We first evaluate the condition:

$$x^0_i + \left(\frac{V(d,p)}{A} + x^0_i - x_0\right)\cdot\left(e^{A(t_1 - t^0_i)} - 1\right) > x_1 \tag{8}$$

and consequently calculate the exit location and time with

$$\{x^*_i, t^*_i\} = \begin{cases} \left\{x_1, t^0_i + \dfrac{1}{A}\ln\left(\dfrac{\dfrac{V(d,p)}{A} + x_1 - x_0}{\dfrac{V(d,p)}{A} + x^0_i - x_0}\right)\right\}, & \textit{condition holds} \\ \left\{x^0_i + \left(\dfrac{V(d,p)}{A} + x^0_i - x_0\right)\cdot\left(e^{A\cdot(t_1 - t^0_i)} - 1\right), t_1\right\}, & \textit{otherwise} \end{cases} \tag{9}$$

with

$$|A| > 0$$

Care must be taken with A values close to zero. This could lead to numerical problems. In practice this applies when the upstream and downstream observed speeds are nearly equal. Note that in these cases the assumption of piecewise constant speeds is justified, and hence equations (7) may be used instead.

NUMERICAL TEST

This section presents the results of a numerical comparison between the trajectory method based on piecewise constant speeds and the newly proposed trajectory method based on piecewise linear speeds. Three types of experiments have been performed. In the first experiment stationary traffic conditions are assumed. The second shows results for single trajectories in non-stationary conditions. The last experiment consists of a series of tests that are based on simulated data.

Example: Stationary traffic conditions

The first experiment is intended as an illustration of the methodological differences between piecewise constant speed based method and the piecewise linear speed based method. In this example, it has been assumed that traffic conditions are stationary, in other words the observed speeds depend on the location of the detector but not on time. Note that these assumptions correspond to the implicit assumptions that are applied if one computes the instantaneous travel time, as explained in the introduction.

Assuming that each link is centered on a detector, the assumption of piecewise constant speeds is illustrated with the dotted line in Figure 4 (bottom), while the assumption of piecewise linear speeds is illustrated with the closed line. The corresponding vehicle trajectories, for different times of departure, are produced by integrating the speed curves over time and are plotted in the top half of the figure. In this simple case the difference between the two methods is clear: the assumption of piecewise linear speeds leads to lower estimates of travel times then those that result when piecewise constant travel times are assumed.

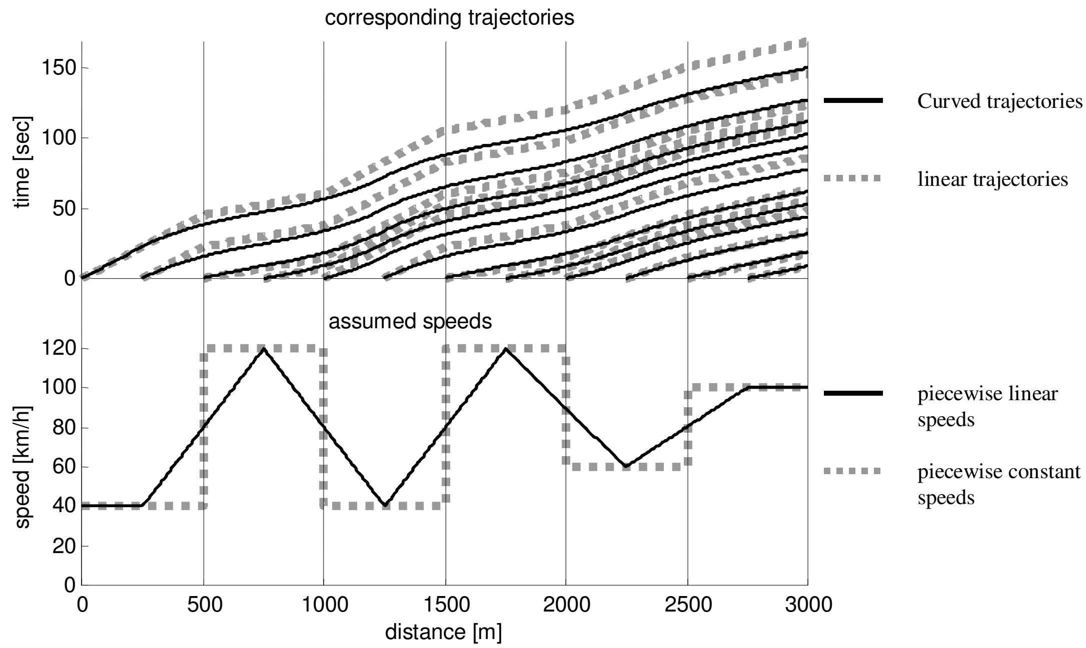


Figure 4: linear versus curved trajectories in the stationary case

Example: Non-stationary traffic conditions

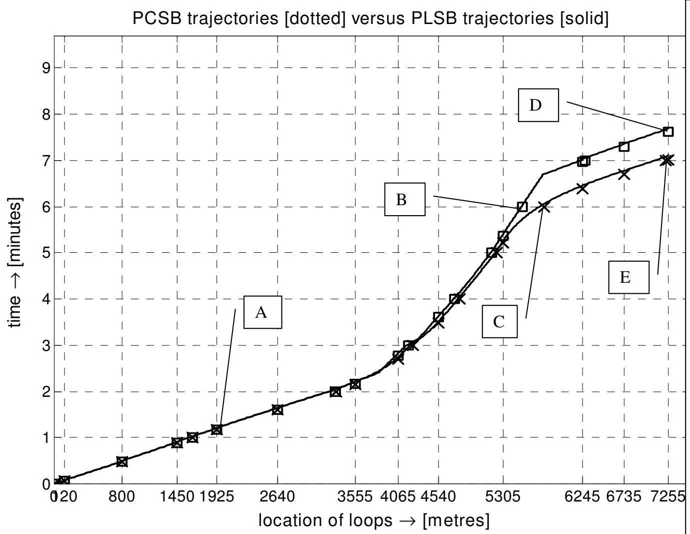
The second experiment is intended to illustrate the methodological differences between the methods in *non-stationary* traffic conditions, and to provide insight in how both methods are used in practice. Figure 5 shows two trajectories calculated with the Piece-wise Constant and Piece-wise linear trajectory method according to the scheme presented in Figure 3. Figure 5 (left) clearly shows how the new PLSB method (solid line) results in smoother trajectories than the PCSB method (dotted line). Again the PCSB method yields larger travel time estimates than the PCSB method.

In the accompanying table (Figure 5 - right) a listing is given of the results of the calculation of both trajectories. Columns four and five show the exit locations and times calculated for the Piece-wise Linear Speed-Based trajectory method. For each step first the *A* parameter is calculated with (6), and consequently the exit time of the vehicle is calculated according to equation (9). As an example exit point C (PLSB trajectory) is calculated as follows:

$$A = \frac{25.0 - 6.11}{6245 - 5305} = 0.0201; \quad \text{Condition (8) holds}$$

$$\Rightarrow \{x_i^*, t_i^*\} = \left\{ 5305 + \left(\frac{6.11}{0.0201} + 5305 - 5305 \right) \cdot \left(e^{0.0201 \cdot (360-313)} - 1 \right), 360 \right\} = \{5788, 360\}$$

Note that the values above are rounded off for ease of reading. The right-most column in the table in Figure 5 provides information whether the trajectory exits the section or the time-period. Columns one to three present the same results for the Piece-wise Const Speed-Based trajectory method, utilizing equation (7).



Example calculation of trajectories in seconds.

PCSB (dotted)			PLSB (solid)		
space [m]	time [s]	action	space [m]	Time [s]	action
0	0	exit section	0	0	exit section
120	4	exit section	120	4	exit section
800	29	exit section	800	29	exit section
1450	53	exit section	1450	53	exit section
1634	60	exit period	1636	60	exit period
1925	(A) 71	exit section	1925	(A) 70	exit section
2640	96	exit section	2640	96	exit section
3323	120	exit period	3327	120	exit period
3555	129	exit section	3555	129	exit section
4065	167	exit section	4065	161	exit section
4189	180	exit period	4236	180	exit period
4540	216	exit section	4540	209	exit section
4730	240	exit period	4790	240	exit period
5167	300	exit period	5226	300	exit period
5305	323	exit section	5305	313	exit section
5534	(B) 360	exit period	5788	(C) 360	exit period
6245	419	exit section	6245	383	exit section
6277	420	exit period	6735	402	exit section
6735	438	exit section	7228	420	exit period
7255	(D) 458	exit section	7255	(E) 421	exit section

N.B. (A) refers to location A in figure to the left

Figure 5: Example of PCBS and PLSB trajectory method for one single trajectory in non-stationary traffic conditions. The table on the right shows the exit points calculated for both trajectories.

Evaluation: experiment based on synthetic data

The new method has been evaluated in a series of experiments based on simulated data. These data have been generated using the microscopic traffic simulation model FOSIM[3]. From these simulated data, harmonic time mean speeds at a number of artificial detector locations and experienced travel times have been derived during 5 independent runs. The network has been specified matching the southbound stretch of the A13 motorway between Delft and Rotterdam (the Netherlands). This stretch contains four on-ramps and four off-ramps, and two weaving sections. The corridor has a total length of 7,3 km and consists of 12 adjacent sections, each equipped with two detectors, measuring 1 minute aggregate flows (veh/min) and one-minute (harmonic) averaged speeds (km/h). The sections have lengths varying from 400 to 800 meters. Five (different) seven-hour simulation runs have been used to compile all the data, totaling in 2085 records. For each simulation run, the traffic demand patterns and the random seed generator has been different, resulting in different but realistic travel time patterns.

Figure 6 (top) shows a typical result. The graphs show the estimated travel times using the PCSB-trajectory method (dotted), the new PLSB-trajectory method (solid) and the reference values obtained from the simulation (grey). The bottom graph in Figure 6 shows the difference between the reference value and the PCSB and PLSB-trajectory methods respectively. Clearly, the new PLSB based estimate reproduces the reference travel time more accurately. As in the stationary case, the PCSB-trajectory method overestimates the travel time, especially during congested conditions. Furthermore, the PLSB method yields a less volatile travel time curve than the PCSB method.

---

[3]FOSIM (Freeway Operations SIMulation) is developed at the Delft University of Technology and has been extensively calibrated for the Dutch Highway Network, see for instance *(18)*

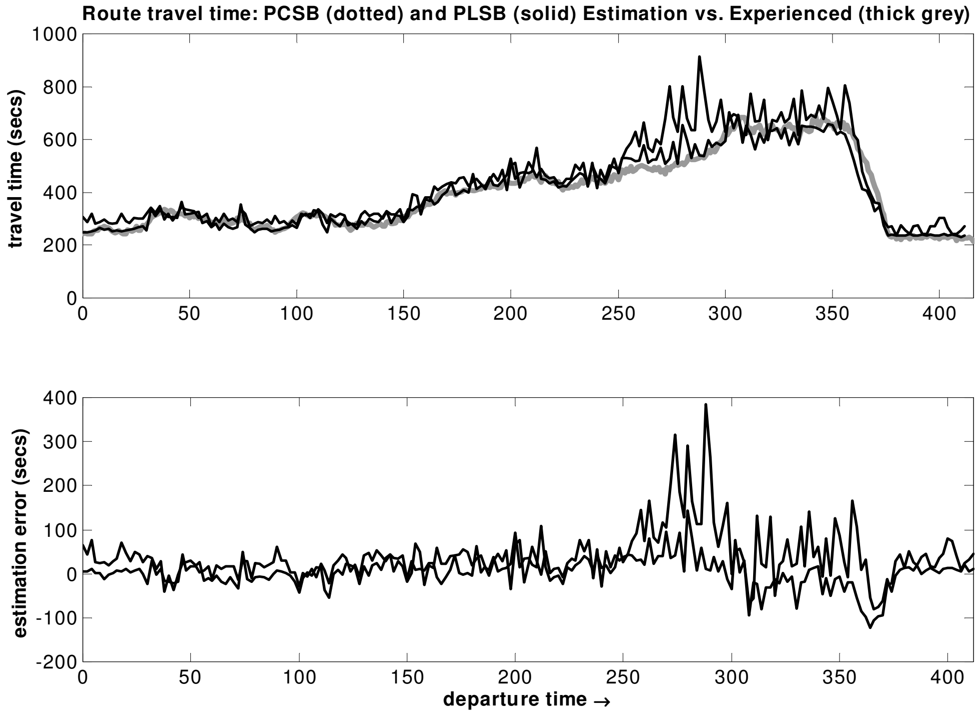


Figure 6: Performance of PCSB- and PLSB-trajectory method on dataset 3. The top graph shows the estimated travel times as a function of departure time. The PCSB (dotted line) shows more bias and erratic behavior then the PLSB (solid line). The bottom graph plots the estimation errors of both methods.

Similar plots can be produced for the other four runs. For a more objective evaluation, we define performance indicators. In these indicators, $\hat{t}(p)$ denotes the estimated travel time for departures in period p and $\bar{t}(p)$ denotes the reference value. The RMSE indicates the overall error

RMSE	(Root Mean Squared Error)	$\sqrt{\frac{1}{P}\sum_{p=1}^{P}\left(\hat{t}(p)-\bar{t}(p)\right)^2}$
Bias	(Bias)	$\hat{\mu}-\overline{\mu}\ ,\ \hat{\mu}=\frac{1}{P}\sum_{p=1}^{P}\hat{t}(p)\ ,\ \mu=\frac{1}{P}\sum_{p=1}^{P}\bar{t}(p)$
RRE	(Root Residual Error)	$\sqrt{\frac{1}{P}\sum_{p=1}^{P}\left(\left(\hat{t}(p)-\hat{\mu}\right)-\left(\bar{t}(p)-\overline{\mu}\right)\right)^2}$
MRE	(Mean Relative Error)	$\frac{100}{P}\sum_{p=1}^{P}\frac{\hat{t}(p)-\bar{t}(p)}{\bar{t}(p)}$

Note that the RMSE can be decomposed in a bias and a root-residual error using $\text{RMSE}^2=\text{Bias}^2+\text{RRE}^2$. Table 1 shows the values of the four performance indicators for both methods on all five datasets. On all performance indicators and on all datasets the new PLSB trajectory method outperforms the PCSB trajectory method. On average the RMSE values for the PLSB method are half of those achieved with the PCSB method, which is a considerable reduction of the error of estimation. For a large part this is due to a reduction of the bias. Applying the PCLS trajectory method significantly reduces the residual error (the remaining error after correcting for bias). In our experiments the PCSB-trajectory overestimates the travel time by nearly 6%.

Table 1: *Performance indicators of PCSB- and PLSB-trajectory methods on all datasets*

	RMSE [s]		Bias [s]		RRE [s]		MRE [%]	
	PCSE	*PLSB*	*PCSB*	*PLSB*	*PCSB*	*PLSB*	*PCSB*	*PLSB*
dataset 1	58,7	29,8	25,8	-0,96	52.7	29.8	5,96	0,96
dataset 2	54,9	33,3	27,1	0,43	47.7	33.3	5,83	1,51
dataset 3	69,7	33,1	30,4	-3,79	62.7	32.9	6,26	-0,12
dataset 4	63,2	32,7	31,7	-4,92	54.7	32.3	6,28	0,32
dataset 5	56,5	32,7	26,4	-3,44	50.0	32.5	5,35	1,12
Mean	60.6	32.3	28.3	-2.54	53.6	32.2	5.94	0.76

CONCLUSIONS

A class of off-line travel-time estimation methods that are based on constructing imaginary vehicle trajectories is investigated. Traditionally these imaginary trajectories consist of a sequence of sections on which a constant speed is maintained that matches the observed speed for that section and time-period. These methods are referred to as the Piecewise Constant Speed Based (PCSB) trajectory methods. This paper replaces the assumption of piecewise constant speeds with the assumption of piecewise linear speeds, where the speed depends on the longitudinal position on the section. This leads to proposing the Piecewise Linear Speed Based (PLSB) trajectory method. Section speeds are assumed to equal a convex combination of the observed speed at the start of the section and the observed speed at the end of the section.

It turns out that based on these assumptions, elegant mathematical expressions can be derived that describe the trajectories in between the two detectors. These equations can be used to directly replace their corresponding equations in the traditional trajectory method. in other words: existing methods can be modified into PLSB trajectory methods with little effort.

A comparison of the accuracy of the PCSB method and the PLSB method has been carried out based on simulated data. This comparison shows that the RMSE value for the PLSB method is about half the RMSE value for the PCSB method, which is a remarkable improvement. After decomposing this RMSE error in a bias and a residual error, it turns out that the PCSB estimates have a significant bias. They overestimate the travel time, especially in congested conditions. In practice the overestimation of the PCSB method might be compensated for by some extent by the fact that many systems use arithmetic time mean speeds rather than harmonic time mean speeds. If no correction is applied the use of arithmetic time mean speeds as a basis for travel time estimation is known to lead to underestimating the experienced travel time.

The largest part of the reduction of the RMSE value is still due to a reduction of the residual error. In other words also if both the PCSB and PLSB estimates are corrected for their bias the PLSB trajectory method performs significantly better.

The improved accuracy of the PLSB method may be used to improve the accuracy of travel time statistics. Alternatively one may choose trade in this approved accuracy for a wider detector spacing in which case considerable cost savings can be reached.

REFERENCES

1. Kraan, M., N.J. van der Zijpp, B. Tutert, T. Vonk, D. van Megen (1999) Evaluatig Network Effects of VMS'S in the Netherlands Transportation Research Record No. 1689, pp. 69-67.
2. Van der Zijpp, N.J. (2002), DelftOD: Estimation Software for Dynamic Origin Destination Tables, www.delftod.tudelft.nl
3. Van Grol, H.J.M., S. Manfredi, and M. Danech-Pajouh (1997), On-line Network State Estimation and Short Term Prediction Deliverable D05.2 of DACCORD, Telematics Application Programme project TR1017, Brussels

4. Kirwan, K., F. Viti, and N.J. van der Zijpp, (2002) On the Predictability of Travel Time on Motorway Networks, Report, TU Delft, pp.1-30
5. Thijs, R., Ch.D.R. Lindveld, N.J. van der Zijpp and P.H.L. Bovy (1999), *Evaluation of travel time estimation and prediction algorithms: Evaluation results from the DACCORD project*, Delft University of Technology, Transportation Planning and Traffic Engineering Section, Delft
6. Ch. D.R. Lindveld, R. Thijs, P.H.L. Bovy, N.J. van der Zijpp, (2000), *Evaluation of online travel time estimatiors and predictors*, Transportation Research Record 1719, paper no. 00-1203, pp 45-53, National Acedemy Press, Washington D.C.
7. Westerman, M. and L.H. Immers (1992) A Method for Determining Real-Time Travel Times on Motorways, Proceedings of the 25th ISATA Conference, Florence, Italy, pp. 221-228
8. Lighthill, M. and G.Whitham (1955) On Kinematic Waves II: A theory of traffic flow on long crowded roads. Proc. R. Soc. London Part A 229 (1178), 317-345
9. Coifman, B., (2002), *Estimating travel times and vehicle trajectories on freeways using dual loop detectors*, Transportation Research Part A 36 (2002) pp 351-364
10. Lindveld, Ch. D. R., Thijs, R., (1999), *On-line Travel Time Estimation using Inductive Loop Data: The Effect of Instrumentation Peculiarities on Travel Time Estimation Quality*, proceedings of the 6th ITS World Congres, Toronto, Canada
11. Van der Zijpp, N.J., and Lindveld, Ch. D.R., (1999), *Evaluation of Queue length display at the Amsterdam Orbital Motorway*, Proceedings of the 6th ITS World Congress, Toronto, Canada
12. Kazimi C., Brownstone, A., Gosh, T.F., van Amelsfort, (2000), *Willingness-to-pay to reduce Commute time and its variance: Evidence from the San Diego I-15 Congestion pricing project*, preprints of the 77th Transportation Research Board annual meeting (CD-Rom), TRB, Washington D.C., USA
13. Petty, K.F., Bickel, P., Ostland, M., Rice, J., Schoenberg, F., Jiang, J., and Ritov, Y., (1998), *Accurate estimation of travel times from single loop detectors*, Transportation Research A, Vol. 32, No. 1, pp 1-17, 1998.
14. Sen, A., Thakuriah, P., (1995), *Estimation of Static Travel Times in a Dynamic Route Guidance System*, Mathematical Computer Modeling, Vol 22, No. 4-7, pp 83-101, 1995
15. Van Arem, B., Van der Vlist, M.J.M., Muste, M.R., Smulders, S.A., (1997), *Travel Time estimation in the GERDIEN project*, International Journal of Forecasting 13 (1997) pp 73-85
16. Kroes, E., Ben-Akiva, Blonk, J., Gieszen, J., and Papageorgiou, (1998), *DACCORD: Overview and Architecture*, presented at the 8th World Conference on Transport Research, Belgium
17. Leutzbach, W, (1987), *Introduction to the theory of traffic flow*, Springer-Verlag, Berlin Heidelberg.
18. Vermijs, R.G.M.M., Schuurman, H., (1994), Evaluating capacity of freeway weaving sections and on-ramps using the microscopic simulation model FOSIM, Proceedings of the second international symposium on highway capacity, Vol 2., pp 651-670