Chapter 2
Travel Time Definitions

Abstract In this Chapter, travel time definitions are analytically presented. Also, a trajectory reconstruction algorithm necessary in order to navigate between different travel time definitions is proposed. The concepts presented in this chapter are aimed to create a conceptual framework useful in comparing travel times obtained from different methodologies. This should be considered as baseline knowledge when going through the whole book.

2.1 Introduction

All the studies dealing with travel time estimation compare the results of their proposed methods to some ground truth travel time data in order to evaluate the accuracy of the method. In fact, some studies are only devoted to that comparison (Li et al. 2006; Kothuri et al. 2007, 2008). The nature of the ground truth travel time data used in each study is varied. For instance Kothuri et al. (2007) uses data obtained from probe vehicle runs, and Kothuri et al. (2008) adds data from the bus trajectories obtained from a GPS equipped bus fleet. In addition to the probe vehicle runs, Sun et al. (2008) also considers travel time data obtained from video camera vehicle recognition. Li et al. (2006) also uses data obtained from vehicle reidentification at control points, in this case by means of toll tags and number plate matching, while Coifman (2002) uses the length of vehicles to reidentify them from double loop detector measurements. In all cases, ground truth travel time data are obtained by directly measuring travel times, whether tracking the vehicle or identifying it at two successive control points. The ways in which these ground truth travel time data are obtained have some implications in the comparison procedure. Coarse comparisons can lead to the counterintuitive results found in literature because what is being compared are apples and oranges.

In the absence of these directly measured travel time data, the alternative can be simulated data using traffic microsimulators (Cortés et al. 2002; van Lint and van der Zijpp 2003). The same care must be taken with the simulated data, and in

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addition, it must take into account that the simulation is a simplification of the real traffic dynamics, and may have not been considering all the complexities of real traffic, resulting in predictable evolution of travel times. This leads to an artificial improvement of travel time estimation methods when ground truth data is obtained from simulation (Li et al. 2006).

The present chapter aims to rigorously present travel time definitions in order to fully understand the nature of each type of measurement. The first step is to differentiate between link (or section) travel time in relation to corridor (or itinerary) travel times. A link is the shortest freeway section where travel time can be estimated, while the corridor refers to the target itinerary whose travel time information is useful to the driver. The common practice (and the case in the present monograph) is to define links limited by a pair of detector sites (this represents only some hundreds of meters in metropolitan freeways), while itineraries are defined, for instance, between freeway junctions. Therefore, an itinerary is usually composed of several links.

2.2 Link Travel Time Definitions

Consider the highway link of length "Δx" and the time interval of data aggregation "Δt" shown in Fig. 2.1. In this configuration, the true average travel time over the space-time region "$A = (\Delta x, \Delta t)$" can be expressed as:

$$T_T(A) = \frac{\Delta x}{v(A)} = \Delta x \cdot \sum_{i=1}^{n} \frac{d_i}{T_i} \tag{2.1}$$

where:

"$v(A)$" is the generalized average speed definition in the region "A", first proposed by Edie (1965).

"d_i" is the distance traveled by the ith vehicle in the region "A".

"T_i" is the time spent by the ith vehicle in the region "A".

Note that two control points at "x_{j-1}" and "x_j" where vehicles are identified are not enough to obtain this true average travel time, as the position of the vehicles travelling within the section at time instants "$p - \Delta t$" and "p" could not be obtained (i.e. points where vehicles cross the time borders of region "A" in the time-space diagram —see Fig. 2.1a). It is possible that the only way to directly measure this travel time is by continuously tracking all the vehicles (or a representative sample of them).

The true average travel time "$T_T(A)$" should not be confused with the arrival based average travel time, "$T_A(A)$", defined as the average travel time in the trip along the whole link "j" of those vehicles that reach "x_j" in the time period "p" (see Fig. 2.1b). This type of ground-truth travel time is obtained from all the direct measurements based on the reidentification of vehicles (number plates, toll tags, bluetooth devices, electromagnetic signatures, platoons, cumulative counts …).

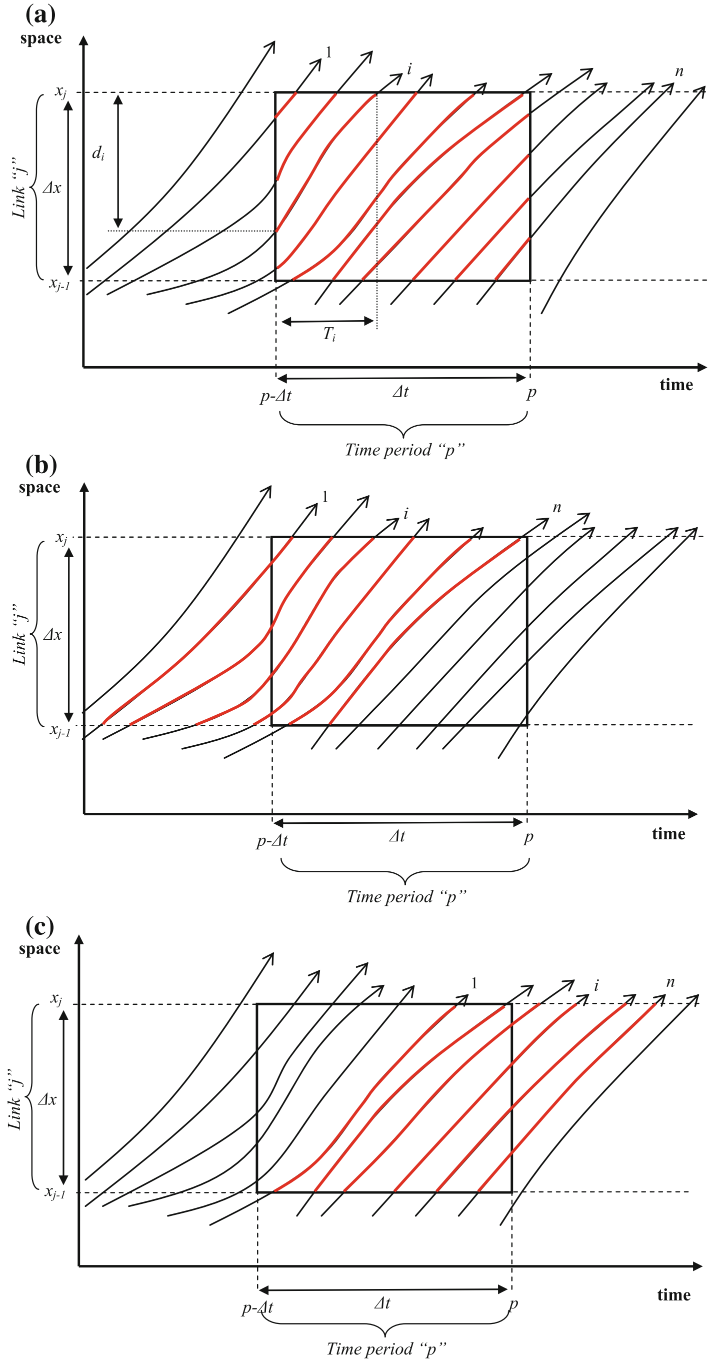

Fig. 2.1 Link travel time definitions in a trajectories diagram. **a** True average travel time. **b** Arrival based average travel time. **c** Departure based average travel time. *Note* In *red*, parts of the vehicles' trajectories considered in the average travel time definitions

As this is the most common directly measured type of travel time, it is sometimes named MTT (measured travel times).

Following the same logic, a third average travel time can be defined. The departure based average travel time, "$T_D(A)$", is defined as the average travel time on a trip along the whole link of those vehicles that depart from "x_{j-1}" in the time period "p" (see Fig. 2.1c).

On the one hand, "$T_A(A)$" considers the last completed trajectories on the highway link, and this may involve considering relatively old information of the traffic conditions on the first part of the link (some of the information was obtained more than one travel time before). On the other hand, "$T_T(A)$" uses the most recent information obtained in the whole link (sometimes these types of travel times are named ITT—instantaneous travel time). However, it is possible that any vehicle has followed a trajectory from which this true average travel time results. Finally, "$T_D(A)$" needs future information in relation to the instant of calculation. Therefore it is not possible to compute "$T_D(A)$" in real time operation. However, there is no problem in obtaining this future estimation in an off-line basis, when a complete database is available, including future information in relation to the instant of calculation. Note that "$T_D(A)$" would be approximately equal to "$T_A(A')$" where "A'" corresponds to the space-time region "A" moved forward one travel time unit in the time axis.

It is also possible, but not so easy, to obtain "$T_A(A)$" and "$T_D(A)$" from "$T_T(A)$". It is only necessary to compute the position of a virtual vehicle within the link as a function of time and considering the average speeds resulting from "$T_T(A)$" at different time intervals. This process, known as trajectory reconstruction, is detailed in Sect. 2.4. Note, that in order to obtain "$T_D(A)$", future "$T_T(A)$" will be needed.

2.2.1 When Travel Time Definition Makes a Difference

The differences between these average travel time definitions lie in the vehicle trajectories considered in the average calculation, "$T_T(A)$" being the only definition that considers all and only all the trajectories contained in "A", while "$T_A(A)$" or "$T_D(A)$" consider trajectories measured outside the time edges of "A", before or after respectively. The magnitudes of these differences depend on the relative difference between "Δt" and travel times. The longer the travel times in relation to the updating time interval are, the greater the difference will be in the group of vehicles considered in each average travel time definition (see Fig. 2.2). "Δt" is a parameter to be set for the travel time information system, with a lower bound equal to the updating interval of the source data (e.g. time interval of aggregation of loop detector data). "Δt" should not be much longer than this lower bound in order not to smooth out travel time significant variations and maintain an adequate updating frequency (i.e. "Δt" should not go above 5 min). Therefore, as "Δt" must be kept small, differences between average travel time definitions depend mainly on travel

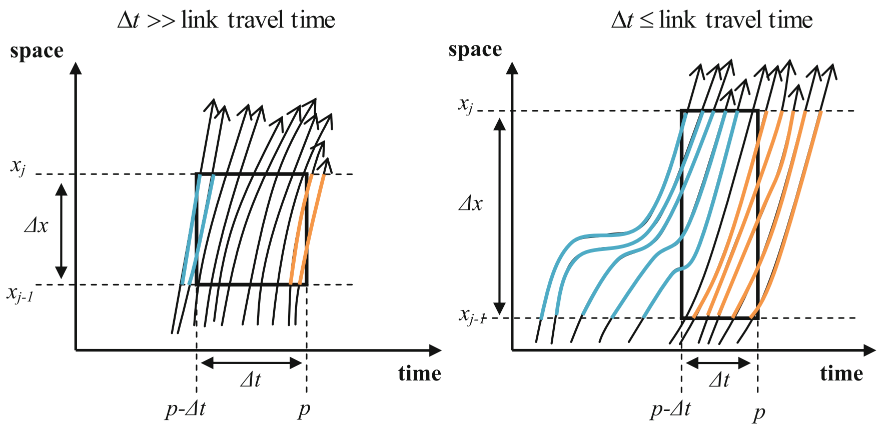

Fig. 2.2 Different trajectories considered in the link travel time definitions. *Note* In *blue*, trajectories considered in the arrival based average travel times but not in the departure based average travel times. In *orange*, the opposite situation, both types of trajectories are only partially considered in the true average travel time. In *black*, shared trajectories

times, which in turn, depend on the length of the highway link, "Δx", and on the traffic conditions.

In situations where link travel times are significantly longer than "Δt", as would happen in the case of long highway links or in the case of congested traffic conditions, the trajectories considered in several average travel time calculations will belong to different groups of vehicles (see Fig. 2.2, right). The case may even arise where none of the vehicle trajectories are shared between different definitions. This would not have any effect on the average travel time in the case of stationary traffic, as the trajectories of the different groups of vehicles would be very similar. However, if a traffic transition occurs in the space-time regions considered in one definition but not in the others, this could result in significant differences between computed average travel times. This is the situation when the definition of average travel time plays an important role. On the contrary, in situations where link travel times are significantly shorter than "Δt" (i.e. short highway links due to high surveillance density and free flowing traffic conditions), the vehicle trajectories considered in one definition but not in the others would be very limited in relation to the total amount of shared trajectories (see Fig. 2.2, left). Therefore, the probability and the relative weight of traffic transitions in this reduced space-time region is very low. This results in differences among definitions as being almost negligible in this case. From this discussion it is concluded than when real-time freeway travel time information is most valuable (i.e. congested and evolving traffic conditions) the different definitions of average travel time play an important role which must be considered.

Also note that it is rather difficult in practice to obtain "$T_T(A)$". However, to obtain "$T_A(A)$", only two vehicle identification points are necessary. As a result of this, there seems to be an interesting possibility of obtaining an approximation to "$T_T(A)$" by using the measurements that configure "$T_A(A)$". This approximation is as simple as only considering the trajectories which have arrived at the downstream control point during "p" time period (i.e. they belong to "$T_A(A)$" group of trajectories) and have departed from the upstream control point also during "p" (i.e. trajectories fully contained in "A" or equally, the shared trajectories between "$T_D(A)$" and "$T_A(A)$", see Fig. 2.2). This approximation would be better as the number of shared trajectories increase. The process would converge to a perfect estimation when all trajectories are shared (i.e. "$T_T(A)$", "$T_A(A)$" and "$T_D(A)$" are equal). On the contrary, in some situations the approximation cannot be applied due to the inexistence of shared trajectories. This would result in the possibility of "$T_A(A)$" being a bad approximation to "$T_T(A)$".

2.2.2 Which Information Is Actually Desired from Real Time Systems?

In a real-time information dissemination scheme, "$T_T(A)$" and "$T_A(A)$" would be available for drivers entering the section at time period "$p + 1$". However, neither the true average travel time, nor the arrival based average travel time at time interval "p" is the information that these drivers wish to obtain. They want to know their expected travel time, and therefore a departure based travel time at time interval "$p + 1$" (sometimes this travel time is known as a PTT—predicted travel time). Therefore, the desired forecasting capabilities of measured travel time must not only span a time horizon equal to the travel time (i.e. in order to obtain the departure based average travel time at time period "p"), but an extended horizon equal to the travel time plus "Δt". This leads to the apparent paradox that while for a longer "Δt"s the true average travel time measurement is a better approach to the departure based average travel time at time period "p" (because more trajectories will be shared), the error made with the naïve assumption of considering "$T_T(A)$" as a proxy for the departure based travel time at time interval "$p + 1$" (the implicit assumption here is that traffic conditions on the corridor remain constant from the measuring instant until the forecasting horizon) usually increases as "Δt" does (because of the extension of the forecasting horizon). Therefore, in some contexts (i.e. transitions, when the implicit assumption does not hold) the averaging of traffic conditions within long "Δt"s could lead to huge variations between adjacent time intervals. This is another reason for "Δt" being kept short.

2.3 Corridor Travel Time

The presented link average travel time definitions are also valid in a corridor context. The main difference in this case is that while the "Δt" remains the same as in the link basis, the increased length of the corridor in relation to the several links from which it is constituted of individual length equal to "Δx_j" results in larger travel times. This implies "$T_T(C)$", "$T_A(C)$" and "$T_D(C)$", where "C" stands for a corridor space—time region "$C = \left(\sum_{j \in corridor} \Delta x_j, \Delta t\right)$" being significantly different in non stationary traffic conditions.

Another issue to consider is how the corridor travel times could be obtained from composing link travel times. In can be easily deduced that corridor "$T_T(C)$" is obtained by simply adding up the links "$T_T(A)$" from the time period of calculation. On the contrary, corridor "$T_A(C)$" and corridor "$T_D(C)$" are not obtained from this simple addition, as it is needed to consider the vehicle trajectory in space and time.

As a conclusion to this definitions section, take into account that the common practice in the real time implementation of travel time systems based on speed point measurements is to estimate link "$T_T(A)$" by means of the available loop detectors, which are added up to obtain the corridor travel time, "$T_T(C)$", to be disseminated in real time. These true average corridor travel times are considered to be the best measurable estimation for the desired departure based average travel time at time interval "$p + 1$", if one wants to avoid the uncertainties of forecasting, and assumes traffic conditions will remain constant. In particular, better than the "delayed" information from arrival based average travel times is "$T_A(C)$" (which could be directly measured in the corridor), provided that "$T_T(A)$" estimations of speed are accurate. Otherwise, this assertion could not be true. Also note that differences between true and predicted travel times depend on the corridor length and on the aggregation period "Δt", which constitute the horizon of the prediction. Therefore, in order to keep differences low and improve the accuracy of the "forecast", an advisable dissemination strategy is to keep corridor lengths as short as possible, while maintaining the interest of the driver on the disseminated information, and frequent updating, so that the time horizon of the prediction is as short as possible.

In the case of off-line travel time assessment, there is no need of trying to infer future travel times, for example by considering the latest information on the corridor as "$T_T(C)$" does. However, it is advisable to assess the real travel time that drivers actually experimented; this means reconstructing their trajectories in order to obtain "$T_A(C)$" from original "$T_T(C)$". These measurements are different in nature, and although they may be pretty similar in a link context, they will be significantly different on a corridor basis and non stationary traffic conditions. The results would be analogous to those obtained from direct measurement from an AVI device, provided that the original true link average travel times were accurate. Therefore, the same process of time and space alignment must be undertaken in a case of comparisons between "$T_T(C)$" obtained from loop detectors and "$T_A(C)$" obtained from AVI direct measurements. This process is described in detail in the next section.

2.4 Trajectory Reconstruction Process

This section aims to present the simple process necessary in order to reconstruct a vehicle trajectory from a speeds field in a discretized space-time plane. In other words, if space mean speeds are available within each link as a function of "x"

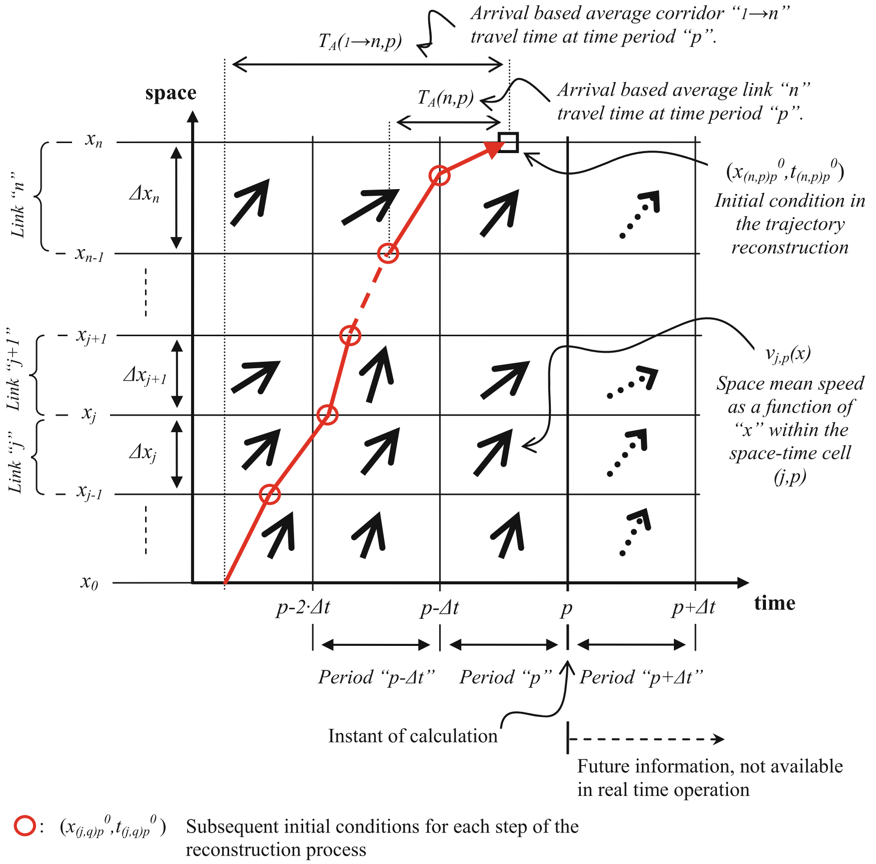

Fig. 2.3 Speeds field in a space-time discretization

(i.e. the position of the virtual vehicle within the link), and this function "$v(x)$", it is assumed that it will remain constant within each time interval "Δt" (see Fig. 2.3). It is possible to reconstruct the trajectories that would result from the arrival based or departure based average link and corridor travel times. It is also possible to obtain the link and corridor average true travel time.

Therefore, the following process is necessary in order to convert true (or sometimes called "instant") travel times into trajectory based travel times. This process is analogous for the arrival based (backward reconstruction) or departure based (forward reconstruction) travel time averages. Taking into account that departure based travel times require future true information, only backwards reconstruction will be described in detail, but the analogous process can be easily derived (van Lint and van der Zijpp 2003).

As van Lint and van der Zijpp (2003) describe, to reconstruct the trajectory of a virtual vehicle [i.e. to obtain the function "$x(t)$"] within a cell (j, q) of the speeds field it is only necessary to solve the following differential equation:

$$\frac{\partial x}{\partial t} = v_{j,q}(x) \tag{2.2}$$

Given "$v_{j,\ q}(x)$", which do not depend on time within a particular cell, and an initial condition "$x(t^0_{j,q}) = x^0_{j,q}$", which in this backward trajectory reconstruction corresponds to the cell exit point of the trajectory. The obtained solution will be valid for that particular cell. In order to obtain the whole trajectory along the link or the corridor to compute the arrival based travel time in time interval "p", it is only necessary to apply the aforementioned process iteratively from the last cell which crosses the trajectory, (n, p) (see Fig. 2.3), until the start of the corridor is reached. At each step the "$v_{j,\ q}(x)$" (which is a function of the cell and of the time interval) and the initial condition must be updated. Note that the initial condition for subsequent cells corresponds to the entrance point in the space-time diagram of the trajectory to the previously calculated cell (see Fig. 2.3). Then, the only initial condition needed to be set is the first one, corresponding to the time instant of calculation of the average corridor travel time. It seems adequate to consider this

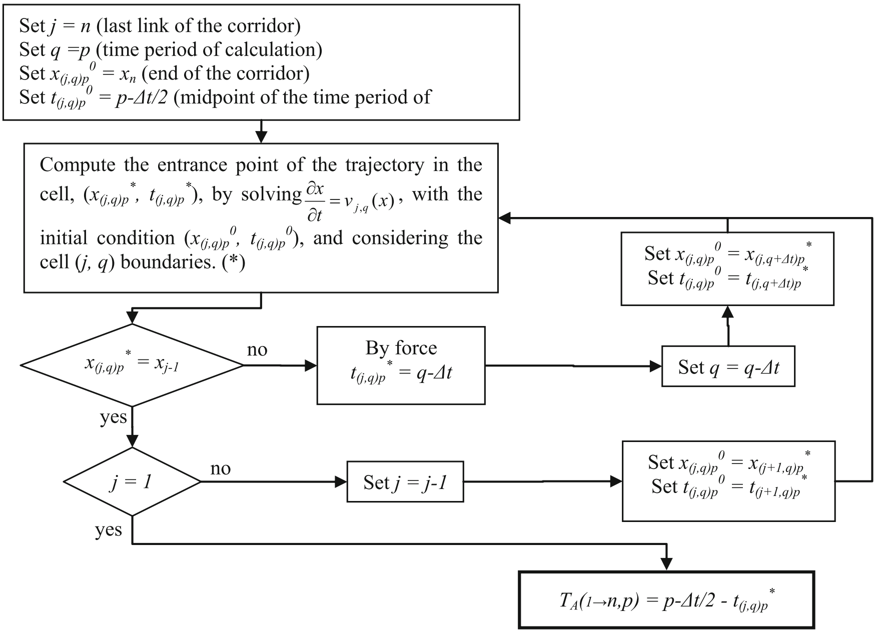

Fig. 2.4 Trajectory reconstruction flow chart. (*Asterisk*) This calculation is explained in detail in the next section for each type of function defining $v(x)$

first initial condition, when computing the arrival based average corridor "*1* $\rightarrow$ *n*" travel time at time period "*p*", as the midpoint of the time interval:

$$x(p - \Delta t/2) = x_n \tag{2.3}$$

The remaining initial conditions, as each cell is confined by space and time bounds, will be defined by the instant the virtual vehicle crosses a link border, or the position within the link where the vehicle undergoes a change of time period.

The whole process for time interval "*p*" is detailed in a flowchart in Fig. 2.4.

The computation of the true average link travel time for link "*j*" and time period "*p*", "$T_T(j, p)$", is simpler as it is only needed to solve Eq. 2.2 without considering the time boundary of the cell. On each link, the initial condition could be "$x(p) = x_j$". Once the equation has been solved and the trajectory function "$x(t)$" is obtained, "$T_T(j, p)$" is calculated by imposing "$x(p - T_T(j,p)) = x_{j-1}$".

Finally, the true average corridor "*1* $\rightarrow$ *n*" travel time for the time period "*p*" is obtained as:

$$T_T(1 \rightarrow n, p) = \sum_{j=1}^{n} T_T(j, p) \tag{2.4}$$

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