

DERIVING INTERSECTION TURNING MOVEMENTS VIA PATH FLOW ESTIMATOR

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Abstract: Intersection turning movement is one of the key components required in a variety of transportation analysis; including intersection geometric design, signal timing design, signal coordination, traffic impact study, and transportation planning. It is generally impractical and expensive to install sensor devices at every single intersection in a general road network to capture a complete set of turning movements. The more appropriate and cost-effective way to satisfy this requirement is to infer the missing data from the available traffic counts. This study proposes using the Path Flow Estimator, originally used to estimate path flows (hence origin-destination flows), to derive not only complete link flows, but also turning movements for the whole road network given some counts at selected roads.

Key Words: Intersection turning movement, origin-destination trip table estimation, path flow estimator, stochastic user equilibrium

1. INTRODUCTION

The estimation of link volumes and intersection turning movements are often required for planning and design of transportation facilities. Regional traffic models (the four-step procedure) can produce the accurate estimates of link flows; however, they are usually not capable of producing reasonable estimates of turning movements due to the aggregation of land uses into Traffic Analysis Zones (TAZs). In other words, the actual paths used by drivers may not be represented in the model. Traditionally, the estimation of future turning movements involves the collection of existing turning movements and the application of factoring algorithms among which Furness Method is the most commonly used (Furness, 1965). Regional traffic models first estimate future link volumes, in and out of an intersection, based on estimated future demands, which is in general difficult to obtain. Then,

the base year turning counts at an intersection are multiplied by factors until the total inflows and outflows of the intersection closely match the estimated link volumes. An obvious limitation of the method is the inapplicability for intersections without existing turning counts. Although recent advanced traffic sensors (e.g., video detection) have the potential to automate such data collection processes, it is still expensive to fully instrument every intersection with sensor. Another drawback of the factoring approach is the insensitivity to changes in the land use patterns and transportation network. The Furness method assumes that future turning movements will be proportional to their existing turning counterparts. However, this is not the case when a major change occurs in the land use pattern and transportation system. In fact, the volume on a particular movement of an intersection that is on a new "preferred" path may dramatically increase due to the corresponding changes of travel behavior.

The objective of this study is to propose a methodology to derive complete link flows and turning movement volumes for the whole network together with an origin-destination (O-D) trip table given some counts at selected roads. The idea originated from the concept of Path Flow Estimator (PFE) first proposed by Sherali *et al.* (1994) as a linear program based on Wardrop's user equilibrium principle (1952). The PFE is a one-stage network observer that can estimate path flows (hence O-D flows) and path travel times from traffic counts on general road networks. It circumvents the difficulties (e.g., nonconvexity, convergence issues, etc.) associated with the bi-level programming approach (Yang *et al.*, 1992; Maher *et al.*, 2001). Bell and Shield (1995) extended the method to the nonlinear PFE, which is based on the stochastic user equilibrium (SUE) assumptions. The logit-based SUE model allows travelers to choose non-equal travel time paths due to imperfect knowledge of network travel times. In addition, the nonlinear PFE yields unique path flows and does not require all links to be measured.

Because a unique set of path flows is readily available from the PFE, it is possible to trace these paths to derive other useful information at different spatial levels. For example, the sum of all path flows from all O-D pairs gives the total flows utilizing the network, the sum of all path flows emanating from a given origin gives a total trip production, and the sum of path flows terminating at a given destination gives a total trip attraction. Flows between an O-D pair can be obtained by simply adding up the flows on all paths connecting that O-D pair. The aggregated link flows are obtained by adding up all path flows passing through a given link. For the turning movements at an intersection, the orientations of links connected to intersection are needed so as to determine the individual turning movement (e.g., left, right, or through movement) from the used paths without a need to expand the network (for representing turning movements).

In this paper, we demonstrate the derivation of turning movements as well as link flows for the whole network via PFE with incomplete traffic data for different network topologies. First, a simple isolated intersection is used to illustrate how PFE derives turning movement flows with entry flows only and both entry and exit flows. Then, we extend the numerical results to a signalized arterial comprised of multiple intersections. Finally, a case study utilizing traffic data collected from the City of Santa Rosa, California, USA is set up to demonstrate the application of the proposed method on the network with both freeways and surface streets. The results also serve to identify the shortcomings and the corresponding improvements for the methodology.

2. METHODOLOGY

2.1 Nonlinear Path Flow Estimator and Formulation

The nonlinear Path Flow Estimator (PFE) was originally developed by Bell and Shield (1995) as a one-stage network observer. It is able to estimate path flows and path travel times using incomplete traffic data from detection devices partially installed in the network. The core component of PFE is a logit-based path choice model in which the perception errors of path travel times are assumed to be independent Gumbel variates (Dial, 1971). The logit model interacts with link cost functions to produce a stochastic user equilibrium (SUE) traffic pattern. Based on the equivalent formulation for a logit-based SUE problem (Fisk, 1980), the PFE formulation can be given as follows.

$$\text{Minimize: } \frac{1}{\theta} \sum_{rs} \sum_k f_k^{rs} (\ln f_k^{rs} - 1) + \sum_a \int_0^{x_a} t_a(w) dw \quad (1)$$

$$\text{Subject to: } x_a = \sum_{rs} \sum_k f_k^{rs} \delta_{ka}^{rs}, \forall a, \quad (2)$$

$$(1 - \varepsilon_a) \cdot v_a \leq x_a \leq (1 + \varepsilon_a) \cdot v_a, \quad \forall a \in M, \quad (3)$$

$$x_a \leq C_a, \quad \forall a \in U, \quad (4)$$

$$q_{rs} = \sum_{k \in K_{rs}} f_k^{rs}, \quad \forall rs \in RS, \quad (5)$$

$$(1 - \varepsilon_{rs}) \cdot z_{rs} \leq q_{rs} \leq (1 + \varepsilon_{rs}) \cdot z_{rs}, \quad \forall rs \in RS, \quad (6)$$

where

- M, U : Sets of measured and unmeasured links
- RS, K_{rs} : Sets of O-D pairs and paths connecting origin r and destination s
- θ : Dispersion parameter
- $\varepsilon_a, \varepsilon_{rs}$: Measurement errors [0,1] for link observations and a target matrix
- v_a, x_a : Observed and estimated flows on link a
- $C_a, t_a()$: Capacity and cost function of link a
- f_k^{rs} : Estimated flow on path k connecting origin r and destination s
- δ_{ak}^{rs} : Path-link indicator: 1 if link a is on path k between origin r and destination s , and 0 otherwise
- z_{rs}, q_{rs} : A priori and estimated O-D flows between origin r and destination s

The objective function (1) has two terms: an entropy term and a user equilibrium term. The entropy term seeks to evenly distribute trips to multiple paths according to the dispersion parameter while the user equilibrium term tends to cluster the trips on the minimum cost paths. Equation (2) constrains the sum of path flow estimates to produce the total link flow estimates for both measured and unmeasured links. Confidence levels can be introduced into (3) to account for the errors of link flow measurements. A more reliable measurement will constrain the estimated flow within a smaller tolerance, while a less reliable measurement will allow a larger range for the flow estimate. For unobserved links, the estimated flows cannot exceed their capacities as indicated by (4). This constraint is incorporated for the same purpose as in the capacitated traffic assignment (Larsson and Patriksson, 1995), which is to

prevent producing unrealistically high link flow estimates. Equation (5) sums up the estimated path flows to yield the O-D flows. Likewise, O-D flow estimates can also be constrained by confidence levels assigned to a target trip table as indicated by Equation (6). These confidence levels can also handle the inconsistency of the observations to a certain extent. By formulating the Lagrangian of PFE's formulation, path flows, link flows and O-D flows can be derived analytically as a function of path costs and dual variables associated with constraints (3), (4) and (6) as follows.

$$f_k^{rs} = \exp \left(-\theta \sum_{a \in M \cup U} t_a \delta_{ka}^{rs} + \sum_{a \in M} \left(u_a^- \delta_{ka}^{rs} + u_a^+ \delta_{ka}^{rs} \right) + \sum_{a \in U} d_a \delta_{ka}^{rs} + o_{rs^+} + o_{rs^-} \right), \quad \forall k, rs,$$

$$x_a = \sum_{rs} \sum_k f_k^{rs} \delta_{ka}^{rs}, \quad \forall a, \text{ and } q_{rs} = \sum_{k \in K_{rs}} f_k^{rs}, \quad \forall rs. \quad (7)$$

For constraints (3) and (6), there are two dual variables for each constraint, representing the lower (u_a^-, o_{rs^-}) and upper (u_a^+, o_{rs^+}) limits. These constraints are inactive if the estimated link and O-D flows fall within the acceptable confidence intervals. The dual variables associated with constraint (4), d_a , appear when links are operated at their capacities.

2.2 Solution Procedure

The solution procedure for PFE is basically based on the iterative balancing technique (Bell and Shield, 1995). Path flows are sequentially scaled to fulfill one constraint at a time by adjusting the dual variables. The solution procedure can be summarized as follows:

Step 0. *Initialization.* Set $n = 0$, $u_{a^+}^n, u_{a^-}^n, d_a^n$ and $x_a^n = 0$ for all links. Set $o_{rs^-}^n, o_{rs^+}^n$ and $q_{rs}^n = 0$, and $K_{rs} = \emptyset$ for all O-D pairs rs . Set all parameters of the next iteration equal to those of the current iteration and then set $n = n + 1$.

Step 1. *Updating Link Costs.* $t_a^n = t_a(x_a^n) - \frac{1}{\theta} d_a^n, \quad \forall a$.

Step 2. *Finding Shortest Paths.* $k_{rs}^n, K_{rs} = K_{rs} \cup k_{rs}^n, \quad \forall r, s$.

Step 3. *Update Dual Variables.*

1. For each measured link ($a \in M$), Equation (3), update link cost (excluding dual variable), and compute flows using Equation (7), If $x_a > 0$ then

$$u_{a^+}^n = \text{Min} \left\{ 0, u_{a^+}^n + \ln \left(\frac{(1 + \varepsilon_a) \cdot v_a}{x_a^n} \right) \right\}, \text{ and } u_{a^-}^n = \text{Max} \left\{ 0, u_{a^-}^n + \ln \left(\frac{(1 - \varepsilon_a) \cdot v_a}{x_a^n} \right) \right\}.$$

2. For each unmeasured link ($a \in U$), Equation (4), update link cost (excluding dual variables), and compute flows using Equation (7), if $x_a > 0$ then

$$d_a^n = \text{Min} \left\{ 0, d_a^n + \ln \left(\frac{C_a}{x_a^n} \right) \right\}.$$

3. For each target O-D flow, Equation (6), update link cost (excluding dual variables), and compute flows using Equation (7), if $q_{rs} > 0$ then

$$o_{rs^+}^n = \text{Min} \left\{ 0, o_{rs^+}^n + \ln \left(\frac{(1 + \varepsilon_{rs}) \cdot z_{rs}}{q_{rs}^n} \right) \right\}, \text{ and } o_{rs^-}^n = \text{Max} \left\{ 0, o_{rs^-}^n + \ln \left(\frac{(1 - \varepsilon_{rs}) \cdot z_{rs}}{q_{rs}^n} \right) \right\}.$$

Step 4. *Convergence Testing.*

$$\text{If } \eta_0 \leq \text{Max} \left\{ \left| u_{a^+}^n - u_{a^+}^{n-1} \right|, \left| u_{a^-}^n - u_{a^-}^{n-1} \right|, \left| d_a^n - d_a^{n-1} \right|, \left| o_{rs^+}^n - o_{rs^+}^{n-1} \right|, \left| o_{rs^-}^n - o_{rs^-}^{n-1} \right| \right\} < \eta,$$

where η_0 is a convergence tolerance (e.g., 10^{-10}) and η is the upper limit of change in dual variables, then set all parameters of the next iteration equal to those of the current iteration, set $n = n + 1$, and go to step 3.

$$\text{If } \text{Max} \left\{ \left| u_{a^+}^n - u_{a^+}^{n-1} \right|, \left| u_{a^-}^n - u_{a^-}^{n-1} \right|, \left| d_a^n - d_a^{n-1} \right|, \left| o_{rs^+}^n - o_{rs^+}^{n-1} \right|, \left| o_{rs^-}^n - o_{rs^-}^{n-1} \right| \right\} \geq \eta, \text{ then}$$

set all parameters of the next iteration equal to those of the current iteration, set $n = n + 1$, and go to step 1; otherwise, terminate.

As can be seen in the above procedure, a column generation (step 2) is integrated into the PFE to avoid path enumeration for a general network. New paths are generated and added into the path set only if the PFE has a difficulty to match the observations or to satisfy the constraints with the current path set (indicated by very large or small dual variables). In other words, only paths necessary to conform the assumed path choice model to the observations are generated.

2.2 Derivation of Turning Movements

In order to derive turning movements at the intersection from path flows, orientations of links connected to the intersection are needed. The orientations of links are defined as in Figure 1. The orientations of links along each path are used to determine the turning movement (e.g., left, right, or through movement). For example, if a particular path precedes the intersection in direction 1 and leaves the intersection in direction 2, the flow on this path is contributing to the amount of flows on northbound right-turn (NBR). According to the convention of link orientation given below, the flow on turning movement constituted by the leading direction g^+ and the leaving direction g^- at intersection i , t_{g^+, g^-}^i , can be computed as follows:

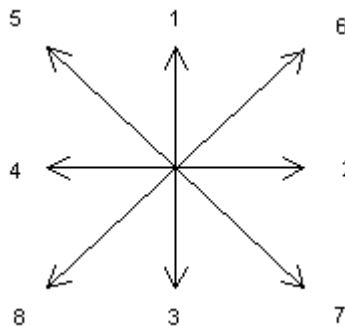


Figure 1 Convention of Link Orientation

- Step 0. Set $t_{g^+,g^-}^i = 0, \forall i, g^+, g^-$, and $rs = 1$.
- Step 1. Set $k = 1$.
- Step 2. Set $\ell = 1$.
- Step 3. For path k , if the ending node of link $a_{k\ell}$ is intersection i , then set $g^+ = \text{orien}(a_{k\ell}), g^- = \text{orien}(a_{k(\ell+1)})$, and $t_{g^+,g^-}^i = t_{g^+,g^-}^i + f_k^{rs}$.
- Step 4. If $\ell < |A_k|$, set $\ell = \ell + 1$ and go to step 3, otherwise go to step 5.
- Step 5. If $k < |K_{rs}|$, set $k = k + 1$ and go to step 2, otherwise go to step 6.
- Step 6. If $rs < |RS|$, set $rs = rs + 1$ and go to step 1, otherwise terminate.

where

- I : Set of intersection nodes
- G_i : Set of movements or directional movements at intersection i
- A_k : Set of links along path k
- f_k^{rs} : Flows on path k connecting origin r and destination s
- t_{g^+,g^-}^i : Flows on movement constituted by leading direction g^+ and leaving direction g^- at intersection i
- $\text{orien}(\cdot)$: Orientation of link

By incorporating the above procedure into PFE, flows on each turning movement at each intersection can be obtained as part of estimation results (together with path flows and O-D flows).

3. NUMERICAL EXAMPLES

3.1 A Simple Isolated Intersection

For the standard four-leg intersection as depicted in Figure 2, there are three movements for each approach (NB, SB, EB and WB), with a total of twelve movements. Traffic counts are also provided in Figure 2. For this network, the turning movements can be treated as a small O-D trip table without route choice. For example, traffic flows on the eastbound right-turn, which is 157 vehicles, are essentially the travel demand from node 1 to node 3. The total demand for this intersection is 5,894 vehicles. The link characteristics of this intersection are provided in Table 1.

Since delay on each movement is different, the probability of selecting each movement should not be equal. In order to account for this non-uniformity, the delay of each movement is assumed to be different but constant according to Table 2. The delays for prohibited movements (e.g., direction 1 and then direction 3) are set to a very large number in order to prevent such illegal movements. These movement delays are also included in the path travel time calculation. The standard Bureau of Public Road (BPR) function, given in Equation (8)

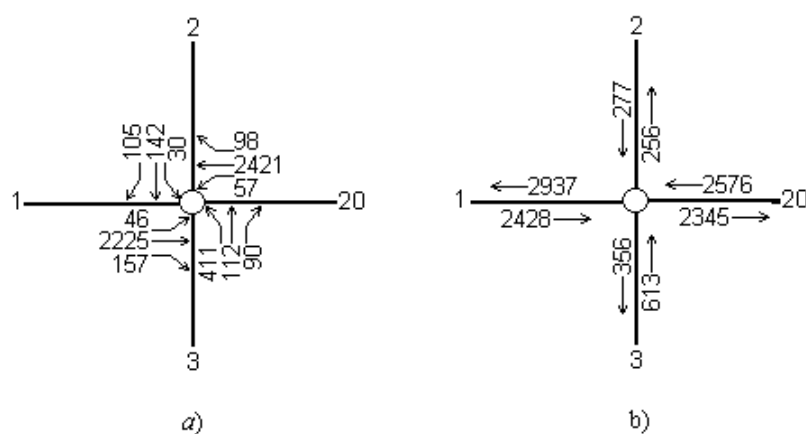


Figure 2 Intersection layout, a) turning-movement counts, and b) entry and exit flows

Table 1 Link Characteristics of an Isolated Intersection

Node		Orientation	Capacity (vph)	Speed (mph)	Distance (mile)	Traffic Count (vph)
From	To					
1	19	2	3,600	35	0.1313	2,428
2	19	3	1,800	25	0.1347	277
3	19	1	1,800	25	0.1313	613
20	19	4	3,600	35	0.1237	2,576
19	1	4	3,600	35	0.1313	2,937
19	2	1	1,800	25	0.1347	256
19	3	3	1,800	25	0.1330	356
19	20	2	3,600	35	0.1237	2,345

Table 2 Intersection Turning Movement Delays (Turn Penalties)

Approach	Delay (hour)			
	1 (NB)	2 (EB)	3 (SB)	4 (WB)
1 (NB)	0.024	0.024	∞	0.017
2 (EB)	0.020	0.030	0.030	∞
3 (SB)	∞	0.017	0.024	0.024
4 (WB)	0.030	∞	0.020	0.030

with $\alpha = 0.15$ and $\beta = 4.0$, is used throughout this study. The dispersion parameter (θ) for this network is assumed to be 30 hr^{-1} , which is the inverse of the average O-D travel time.

$$t = t_a^0 \left(1.0 + \alpha \left(\frac{x_a}{C_a} \right)^\beta \right) \quad (8)$$

Two sets of traffic counts, (1) entry flows only and (2) entry and exit flows, are used to examine the quality of information contained in traffic counts to the accuracy of turning movement estimates. It is assumed that the observations were obtained without measurement error and they are consistent. Furthermore, the true turning movement volumes are as observed. Accuracy of the estimates, therefore, can be defined by the root mean square error (RMSE) as follows:

$$RMSE = \sqrt{\frac{1}{N} \sum_{n=1}^N (x_{est}^n - x_{obs}^n)^2}, \quad (9)$$

where N is the number of observations, x_{est} and x_{obs} are the estimates and observations respectively. PFE aims to reproduce the observed flows for links with measurement and to produce less than capacity flows for links without measurement. The estimation results using the first and second sets of traffic counts are respectively presented in Tables 3 and 4 with their corresponding RMSEs.

Table 3 Estimation Results using Entry Flows only ($RMSE_{OD} = 1,314.04$)

From/To	1	2	3	20	Total
1		915	709	805	2,428
2	89		79	110	277
3	245	168		200	613
20	846	717	1,013		2,576
Total	1,180	1,800	1,800	1,114	5,894

Table 4 Estimation Results using Entry and Exit Flows ($RMSE_{OD} = 160.95$)

From/To	1	2	3	20	Total
1		171	194	2,063	2,428
2	164		8	105	277
3	425	11		177	613
20	2,348	74	154		2,576
Total	2,937	256	356	2,345	5,894

The results are presented in an O-D trip table format, which indicates the amount of travel demands from one node to the others. Considering the first set of traffic counts, PFE can match the observations as well as the total demand of this network perfectly. However, due to insufficient information regarding the exit flows, the best estimates on exit links are constrained by their capacities. Besides, the amount of observed flows on the entry links seems to be uniformly distributed among all movements (due to the nature of objective function, maximum entropy). As can be seen, the estimated and true O-D flows (turning movements) are rather different as indicated by a RMSE of 1,314.04.

By including the exit flows into the estimation process, PFE is able to match both entry and exit flows. The quality of O-D trip table is generally improved as indicated by the reduction in RMSE from 1,314.04 to 160.95. However, the true spatial pattern of O-D trip table cannot be captured due to the under-determinate nature of the problem (i.e., the number of unknowns is less than the number of linearly independent equations). Although, the entropy function is used as the objective function to select the most probable flow pattern, it is apparent that the true O-D matrix is seldom the most probable one. In such a situation, a better turning movement delay representation at the intersection may help us to obtain a better estimate.

3.2 A Signalized Arterial

This example considers an arterial street connected by a series of signalized intersections. The layout of this arterial as well as the traffic counts are provided in Figure 3. Traffic counts were collected during the evening peak hour. Data preprocessing was required to remove errors and inconsistencies in order to avoid getting erroneous results. This network involves 8 signalized intersections, 50 links, 18 external stations, and 306 O-D pairs. The total demand of this network is 12,110 vehicles. The dispersion parameter of this network is assumed to be 8 hr^{-1} . In addition, it is assumed that travel delay patterns at all intersections are identical to the one presented in the previous example. Traffic counts on links originating from and destined to the external stations, 36 out of 50 links, are used as the observations. The O-D demand estimates are presented in Table 5.

As can be seen from Table 5, the total demand of this network can be estimated correctly since all entry and exit flows are provided. Similar to the previous example, the observations on entry and exit links represent trip productions at origins and trip attractions at destinations in the sense of a trip distribution procedure. These numbers are exactly matched as well since they are used as observations. Because of the unavailability of the true O-D trip table, we do not report the RMSE for the O-D estimates; instead we report the RMSE for the estimated turning movements. The estimated turning movements are depicted in Figure 4.

For this case study, it is found that the turning movement estimates on the major street are fairly acceptable while those on the minor streets are not, especially for the through movement. In general, the through movement estimates on the minor streets are underestimated while their left- and right-turn counterparts are overestimated. This is due to the fact that there is only one path traversing the through movement on any minor streets (e.g., path from node 3 to node 2 in Figure 3) while there is at least one path traversing the other movements (from minor street to major street). In addition, since the main traffic

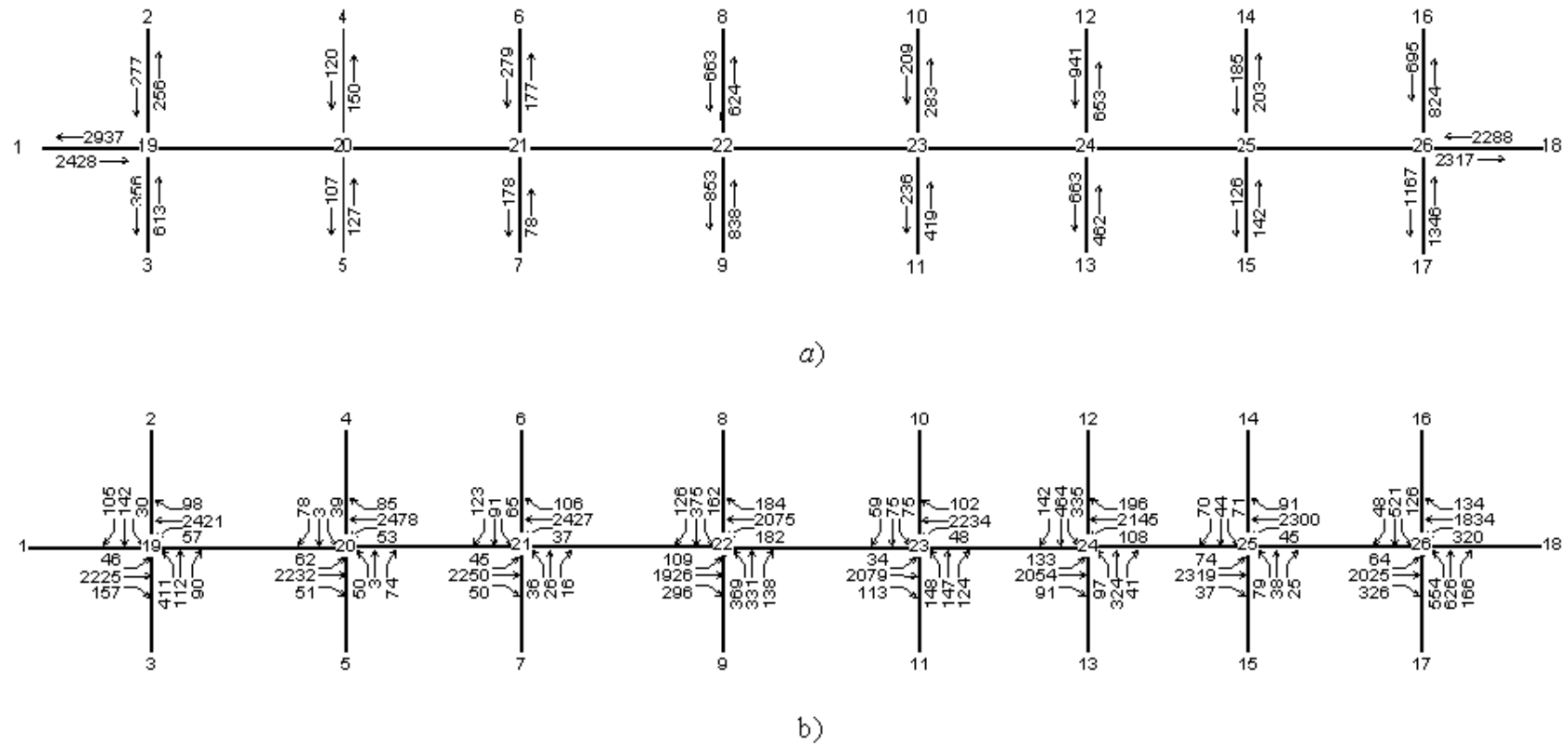
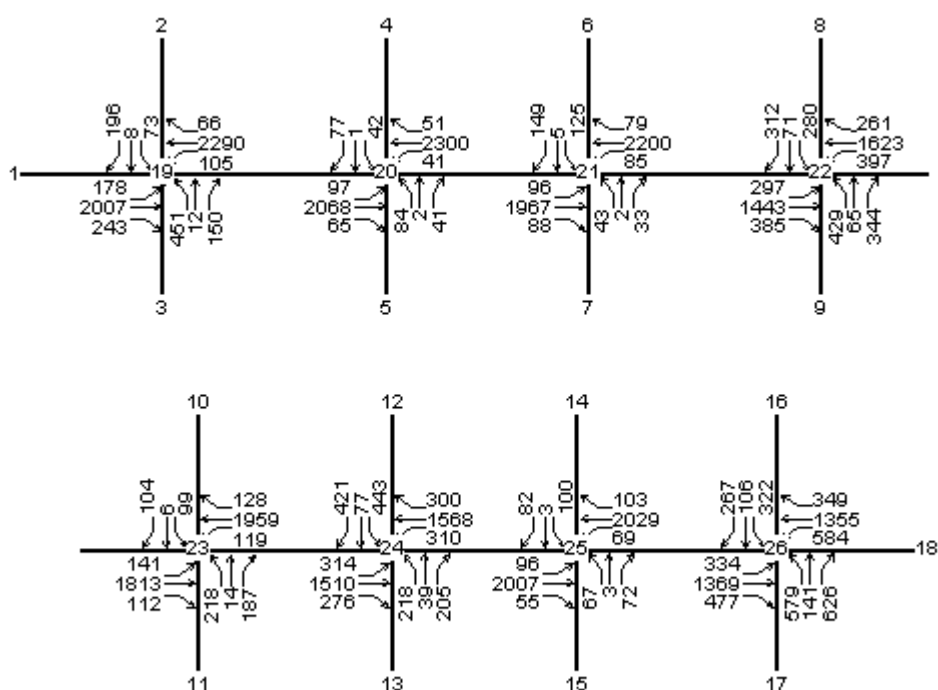


Figure 3 Layout of Arterial Network, a) entry and exit flow observations, and b) turning movement counts

Table 5 O-D Trip Table Estimated using Observations on Entry and Exit Links

From/To	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Total
1		178	243	87	59	83	76	238	308	79	62	152	133	33	18	104	148	426	2,428
2	196		8	3	2	3	3	9	11	3	2	5	5	1	1	4	5	15	277
3	451	12		6	4	6	6	18	23	6	5	11	10	2	1	8	11	32	613
4	71	2	3		1	2	2	5	7	2	1	3	3	1	0	2	3	10	120
5	78	2	4	2		2	2	5	7	2	1	3	3	1	0	2	3	9	127
6	133	4	6	3	3		5	17	23	6	5	11	10	2	1	8	11	31	279
7	39	1	2	1	1	1		5	6	2	1	3	3	1	0	2	3	8	78
8	260	7	12	6	5	10	11		71	19	15	37	32	8	4	25	36	103	663
9	357	10	16	9	7	14	15	65		24	19	45	40	10	5	31	44	127	838
10	61	2	3	1	1	2	3	12	18		6	15	13	3	2	10	15	42	209
11	129	4	6	3	2	5	6	25	38	13		28	25	6	3	19	27	79	419
12	221	6	10	5	4	9	10	43	65	24	23		77	20	11	63	90	259	941
13	114	3	5	3	2	5	5	22	34	13	12	39		9	5	29	42	120	462
14	31	1	1	1	1	1	1	6	9	3	3	11	12		3	15	22	63	185
15	25	1	1	1	0	1	1	5	7	3	3	9	9	3		11	16	45	142
16	93	3	4	2	2	4	4	18	27	10	10	34	35	13	8		106	322	695
17	202	6	9	5	4	8	9	39	59	22	21	74	76	27	18	141		626	1,346
18	473	14	22	11	9	19	20	92	139	52	48	172	178	64	42	349	584		2,288
Total	2,937	256	356	150	107	177	178	624	853	283	236	653	663	203	126	824	1,167	2,317	12,110

Figure 4 Estimated Turning Movements for Arterial Network ($RMSE_{turn} = 209.048$)

stream is on the major street, the contribution of flows from one minor street (through movement) to match the observation on the opposite minor street is always dominated by the flows from the major street especially when the turn penalties at intersection are likely to be misspecified. The comparison of the observed and estimated turning movements is shown in Figure 5. Each point represents the volume of an estimated-observed turning movement pair. The data points along the 45-degree line represent a perfect match. Although PFE can reproduce link traffic counts perfectly, the spatial distribution of turning movements (also pattern of O-D demands) is difficult to capture with this limited amount of information provided.

3.3 Mixed Freeway and Surface Streets

The City of Santa Rosa is located approximately 60 miles north of San Francisco. The study area, depicted in Figure 6, occupies the southeast quadrant of the city, where major changes in land use and transportation network are planned. Several major residential projects throughout the area are being proposed. In addition, a major arterial street will connect the east and south ends of the study area. There are 23 traffic analysis zones (TAZs) including the external stations, which result in a total of 506 O-D pairs.

Link traffic counts over a period of 24 hours were collected on average weekdays with electronic devices. Link volumes of the evening peak hour (5pm to 6pm) are used for this study. Due to limitation in the number of devices, not all links were collected on the same day. In addition, link volumes on some of the smaller local streets were not collected. There are 91 out of 174 network links with traffic counts, which is approximately 52 percent of the total number of links. Turning movement counts are collected later and used to validate the turning movement estimates. There is no information relative to movement delay. The dispersion parameter for this network is assumed to be 18 hr^{-1} , which is the inverse of the average O-D travel time. Since the traffic counts are highly inconsistent throughout the network (e.g., the summation of inflow is not equal summation of outflow), the error bound for all links are arbitrarily set at ± 20 percent, which is slightly larger than the normal value.

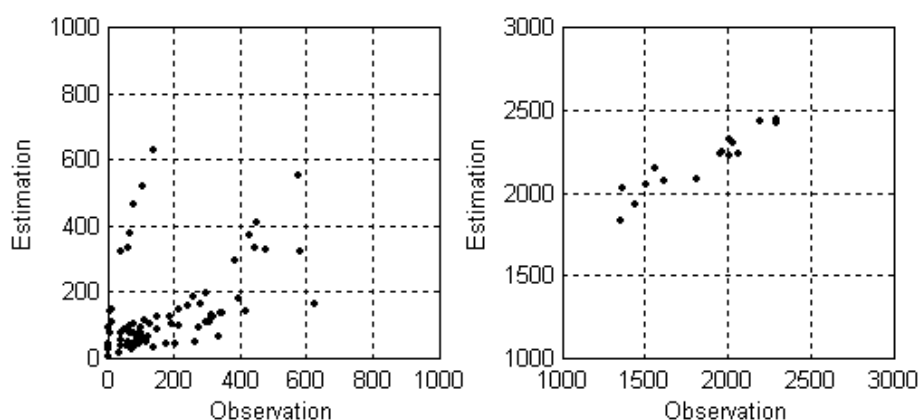


Figure 5 Comparison between derived and observed turning movements

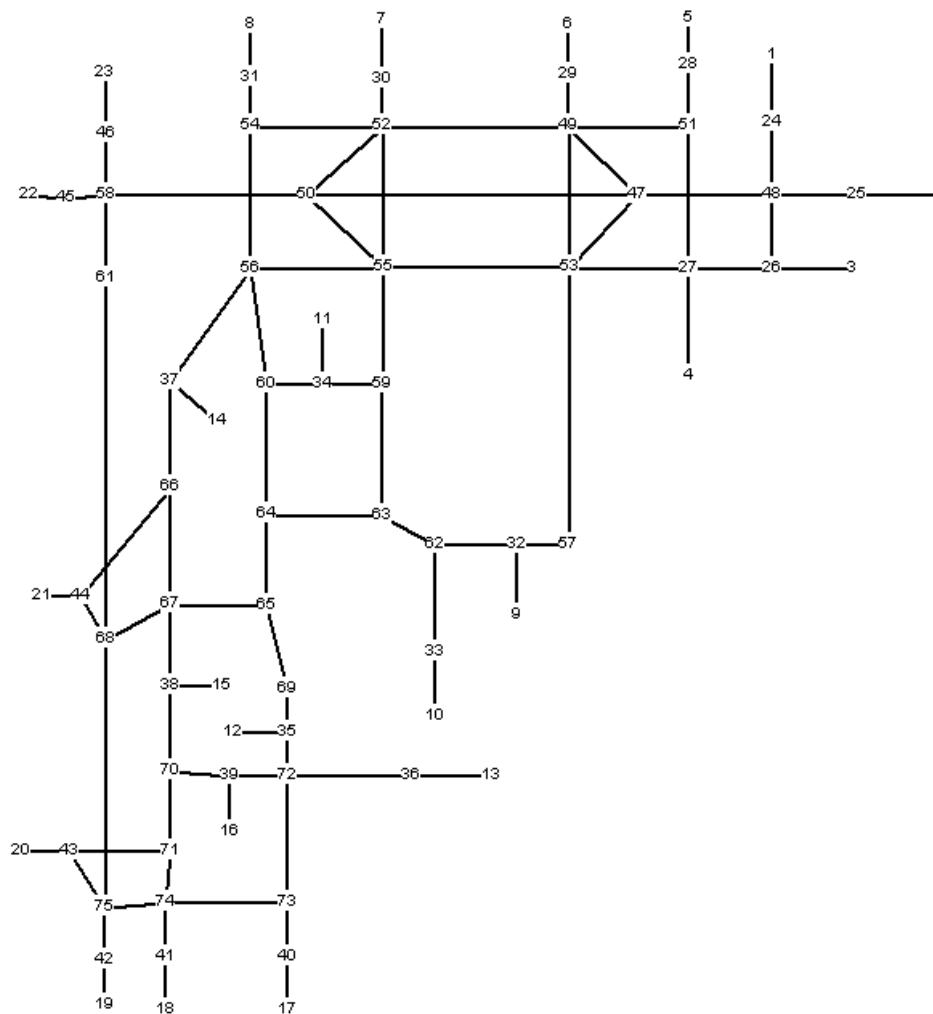


Figure 6 Layout of mixed freeway and surface streets, City of Santa Rosa, CA, USA

The accuracy in terms of link flow estimates is presented in Figure 7. As expected, PFE can produce the traffic flows within the acceptable error bounds (± 20 percent). The estimates for the turning movements for the intersections with observations are presented in Table 6. In general, the turning movement estimates derived from PFE are acceptable for movements with higher volumes, particularly the through movements. However, PFE has a difficulty to estimate the left- and right-turn movements, and those with low volumes. Using this set of traffic counts, the turning movements are derived with a RMSE of 150.187.

A close examination on the actual turning movement counts and PFE outputs reveals potential reasons and the areas to improve the quality of the turning movement estimates as well as O-D trip table. First, network representation as well as intersection signal timing are crucial to the accuracy of the estimation. Zones and streets serving up to a certain number of flows should be included in the network representation. For example, in this case study, several residential zones and the streets that connect them to a major arterial are not included in the network representation, which inevitably creates inconsistencies in the estimation of turning movements at intersections upstream and downstream of these residential zones. In turn, these

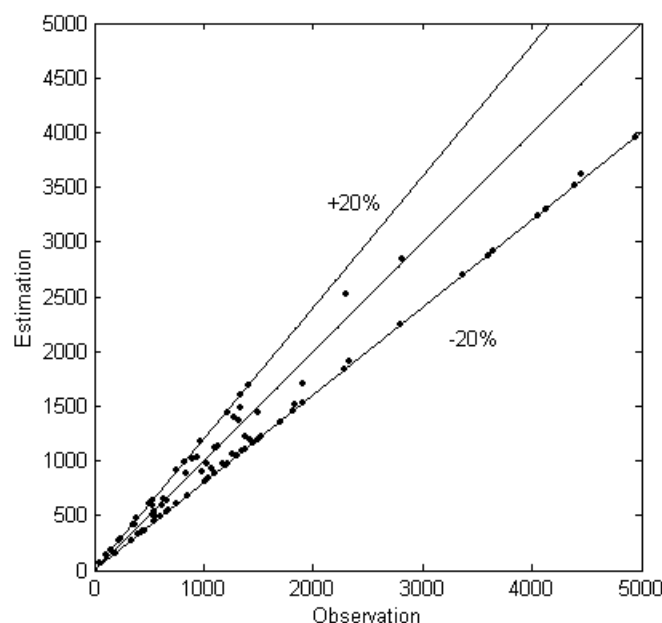


Figure 7 Comparison between estimated and observed traffic counts

Table 6 Comparison of Turning Movement Estimations (RMSE = 150.187)

Intersection		NBL	NBT	NBR	SBL	SBT	SBR	EBL	EBT	EBR	WBL	WBT	WBR
62	Estimation	143		42					312	139	18	203	
	Turning Movement Counts	83		71					918	108	88	568	
63	Estimation				112		253	204	340			284	62
	Turning Movement Counts				34		380	197	489			291	25
64	Estimation		478	447	97	546					421		117
	Turning Movement Counts		483	587	41	612					574		54
72	Estimation	109	729	3	26	772	333	293	30	185	9	27	27
	Turning Movement Counts	115	921	21	4	889	254	379	24	127	11	22	19
73	Estimation	220	756			773	192	84		51			
	Turning Movement Counts	181	1,045			944	79	26		95			

aforementioned factors imply the importance of path set used in the estimation. Different path sets, generated either by a path enumeration or a column generation, certainly lead to different estimates of which their accuracies might be totally different. Second, traffic counts on links connecting to network gateways (i.e., end nodes) are also important to the quality of the estimation. They ensure the accuracy of the estimation along major roadways. Third, the fact that link traffic counts used were not collected at the same time also represents an important source of errors (inconsistency problem) in this case study.

4. CONCLUSIONS

In this paper, we demonstrated how to derive complete link and turning movement estimates for the whole network together with O-D trip table given some traffic counts via the nonlinear Path Flow Estimator (PFE). In particular, we suggested an approach to derive intersection turning movement flows using the unique path flows obtained by solving the one-stage PFE. These intersection turning estimates are key inputs required in a variety of transportation analysis. The results obtained from this study for different network topologies are encouraging. However, additional work is needed to refine the PFE to better model the turning movements, which will hopefully contribute to the improvement of the quality of O-D estimates as a whole.

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