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Novel Estimation Method of Community AADT and VMT via Circuit Network Models and Simulation

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***Abstract*—Annual Average Daily Traffic (AADT) and Vehicle Miles Traveled (VMT) of traffic network are very important data for the plan and decision making. How to estimate AADT and VMT on local area roads is a long-time existing problem due to lack of traffic monitor counts. This paper presents a novel approach to the community area AADT and VMT estimation by developing circuit network model and simulation to solve this difficult problem for community local traffic network roads. The circuit network model is developed based on the community traffic network, and has three sub-models combined by the least squares method (LSM). These sub-models respectively represent even, local and separate distributions of the entrance traffic flows among households in a community. The method is well validated by sampled measurement data and circuit network simulation results. In addition, it is discovered that the total entrance traffic amount is strongly related to the total number of households in communities. Thus, it makes the new method feasible to estimate the AADT and VMT on community local area roads even without any measurement in future. The proposed method not only can provide accurate estimate, but also can dramatically reduce the labor load and cost of traffic counts.**

I. Introduction

Information about vehicle miles traveled (VMT) and annual average daily traffic (AADT) is very important to transportation planning and decision making, revenue allocation, accident analysis, highway facilities design and operation analysis, energy consumption analysis, vehicle emissions estimate, air quality analysis, traffic impact assessing, budget estimate, road development and maintenance plan [1-4]. Thus, the AADT and VMT are the essential and important measures to evaluate the utilization of traffic road network. The VMT refers to total miles travelled by all vehicles on a road network. It is required in the Highway Performance Monitoring System (HPMS) by the Federal Highway Administration (FHWA) [3, 5]. Therefore, the accurate VMT is needed for states and the FHWA.

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Currently the VMT is estimated by two kinds of methods: traffic-count-based and non-traffic-count-based methods ([1, 2] and references therein). The former kind of methods first use the traffic counts to calculate or estimate the AADT of a road, then multiply it and its road length for this road VMT, and accumulate the multiplication into the overall estimated VMT of the region [1, 2, 5]. On the other hand, the latter kind of methods use non-traffic data, usually socioeconomic data (e.g., fuel sales, populations, etc.) to estimate VMT [1, 2, 6]. Kumapley and Fricker discussed many methods for estimating the AADT and VMT [1, 7]. Liu and Kaiser proposed several statistical models to predict truck VMT growth by using socioeconomic data with transportation system supply variables [6]. PTV developed the VISUM software for traffic analysis and planning, however, it is not for AADT and VMT estimate [8]. Recently, Yang, Wang and Bao proposed a local AADT estimation with effective smoothly clipped absolute deviation penalty procedure to select significant variable based on regression models [9]. Currently, the most common approach to estimate VMT is traffic-count-based because of the accuracy need. The estimation accuracy will increase as the number of counters/monitors increases. However, only a part of traffic network is monitored due to the cost. Thus, the sampling method is commonly used to set traffic counters.

In 2009, FHWA [10] listed new practices of some states to report local area AADT and VMT. New practices divide original road classes into more sub-classes by increasing class parameters. Among that, some most noteworthy state activities on methodology are as follows [10]:

(a) Georgia State classifies roadways statewide into 16 groups by population and road surface, and then randomly samples the road sections of non-Federal-aid roads annually.

(b) Kentucky State develops a factor curve to describe the relationship between local roads AADT average and minor collectors AADT average by county. The data to determine relationship are from random samples of local roads and (minor) collectors.

(c) New York State proposes a sample-based count program that divides the rural and urban by their volume into 14 domains, thus reducing the total required sample number for the required AADT and VMT accuracy.

The common feature among them is to divide the road network into small groups, then to sample on each small group, that leads to the total sampling number reduction, and finally to apply the average of the sampled AADT in a group to all roads in this group. The progress and improvement have been made along this line. However, the existing difficulty and an open problem are (i) how to divide groups based on the traffic data, and furthermore (ii) how to identify which group a road belongs to without its road traffic account data.

Moreover, the sampling method accuracy depends on the homogeneity of the road functional class [1]. However, many factors can make the heterogeneity, e.g., different features among roads in communities and high-ways. Furthermore, based on the probability theory and central limit theorem, the accuracy does heavily depend on the number of samples, i.e., a large number of sampling is necessary for a certain level of accuracy.

It is a national recognized long-time existing difficult problem to estimate AADT and VMT on local roads because these roads lack traffic monitors [1, 10, 11]. On the other hand, a high percentage of roads are local roads. For example, in the North Carolina, 72% of statewide road mileages are of local area roads. Thus, the local roads have a non-negligible VMT contribution to the statewide VMT, even though their AADTs may be not high. Lack of traffic monitoring data is the major reason for the difficulty of the AADT and VMT estimation on local area roads. Therefore, the accurate estimation on the local roads is not only important but also a challenge to the VMT and AADT estimation. How to estimate the local AADT and VMT is a tough urgent statewide and nationwide issue due to lack of monitoring and counters to provide measurements.

Recently, we proposed a model method by utilizing the shortest path, turn penalty and probability to traffic network models for estimating the community area AADT and VMT [11, 12]. It is noticed that how to raise the estimation accuracy is still a challenge. Further investigation on new approaches and methods to accurately estimate them is needed.

In this paper, we are the first to propose a novel approach to estimate the AADT and VMT on community traffic network roads via the circuit network model and its simulation in the literature. We focus on residential community area roads because the residential community area roads are the major part of road network in most areas of cities, and they usually have no any traffic counters. The community circuit network model and its simulation for the AADT and VMT are developed based on the community traffic network. With the Least Squares Method (LSM), the model combines three sub-models where these new sub-models respectively represent even, local and separate distributions of the entrance traffic flow sources among the households in the community. These sub-models reflect the traffic flow characteristics in the sense of statistics and the definitions of the AADT and VMT. Therefore, it can dramatically reduce the labor load and cost of traffic counts, and can efficiently estimate the community area AADT and VMT for the statewide estimation.

Up to the best of our knowledge, it is the first time to utilize the circuit network and Kirchhoff law to estimate AADT and VMT of the traffic network in the literature. The method is validated by sampled measurement data and circuit network simulation results. In our test experiments, their statistical relative errors are less than 5% for the mean and about 10% for the weighted average at all checked points.

Furthermore, we also find that the total entrance traffic amount in a community is strongly related to the total household number in this community. Thus, it makes feasibility for this new method to predict the AADT and VMT even without community traffic measurement data in future.

The rest part of this paper is organized as follows. Section II describes the data measurement in communities and finding. In section III, we present the circuit model with three sub-models for community area AADT and VMT estimations via the circuit network approach. Section IV verifies the proposed approach and method for the AADT estimation by experiment measurements. Finally, Section V concludes the paper. Due to the page limit, some details are omitted here.

II. Community Traffic Data Collection and its Finding

In order to analyze the AADT and VMT of residential community roads and verify the proposed new method, we develop a scheme to collect traffic data of sampled communities in NC Mecklenburg County, US as follows:

(a) We divide Mecklenburg county map into 400 (20×20) small areas, and randomly select them for field tests;

(b) In the randomly selected areas, we further select residential communities, and measure the traffic amounts at all entrances and some sampled roads of the communities;

(c) The traffic amounts are counted at least for two continuous days as the FHWA Traffic Monitor Guide [5] instructed, and moreover, most of them are counted for seven continuous days;

(d) The raw counting data are converted to the AADT by the seasonal factors and the axle factors to follow the FHWA Traffic Monitor Guide [5].

From the collected data, we find that the relationship between the household number and the total entrance AADT of each community is very significant as shown in Fig. 1, where the x-axis is the household number, and the y-axis is the total entrance AADT of each community.

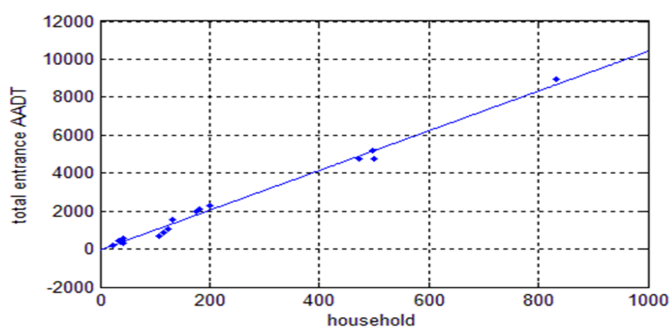

Fig. 1. Linear regression between household number and total entrance AADT of communities

To have a relationship is an imaginable fact. But, it is so interesting to find it as linear in tests. The regression model in Mecklenburg County shows as:

$$TotalEntranceAADT = 10.343 \times Household \quad (1)$$

where its p-value < 0.0001, and $R^2 = 0.9951$. It indicates that the linear model (1) is significant enough to fit the relationship. It means that the total entrance AADT of a community can be estimated by the number of household, while the latter is easier to be obtained in the GIS (Geographic Information System) database than the former which needs the field measurement. For different cities, some sampling may be needed to identify their relationship.

III. AADT and VMT Estimation via New Approach of Circuit Network Models

In this section, we present a new approach for the AADT and VMT estimation on the local roads of communities by circuit network models.

3.A. Traffic Network and Circuit Network

We use the current flow in the circuit network to represent the traffic flow in the traffic network. Thus, we model the circuit network to have the same topology as the considered traffic network to investigate, estimate and predict the AADT and VMT, where the circuit branches represent traffic roads, and the current amount on a circuit branch represents the traffic amount on this corresponding road, respectively.

We notice that the VMT on a road is calculated by the multiplication of its AADT and road length. Therefore, if we set the circuit branch resistor value as same as the road length, then the voltage across the resistor of a branch is exactly the VMT on this corresponding road in view of the Ohm's law. Then the overall VMT on a traffic network acquired by summing up the VMTs of all roads in this network is equal to the sum of the absolute values of voltages on all of this network braches.

The validity basis to utilize the circuit network for the traffic network study is that the traffic flow on a network obeys the rule exactly similar to the Kirchhoff's Current Law (KCL) which the circuit current must obey, because they both obey the principle of continuity.

Based on the noticed traffic facts, we find that the majority amount of traffic flow on the community network is controlled by the entrance traffic amount of the network, i.e., the "pure" internal traffic flow amount from one household driving to another household in the same community may be negligible compared with the traffic amount at the community entrances. The entrance traffic flow on a community network (either entering or out of) is distributed among the households in this community in statistics, simply based on the fact grounds and in view of available data. In view of the fact that the AADT and VMT on a road are defined without distinction of the traffic direction on this road, we model the traffic flow as one direction as either entering or going out of the community, with combining together the both directions traffic amount at the entrance. The entrance traffic flow is set as a current source at the entrance for the circuit network, all with a same direction, say entering the network without loss of generality. Based on the KCL, the circuit network must have the same total amount of all sink currents as the total amount of all current sources at the entrances entering this circuit network. This equivalent traffic flow should be distributed to each household on the traffic network of this community.

Then, the key question is how to distribute this total sink current amount along the network branches based on the entrance current sources. For simplicity by the statistics, we let each branch have an average sink current source at its branch mid-point to the ground, respectively. It means that each branch should have a sink current source based on the household distribution at this road branch in the traffic network. For a simple illustration, a real community with two entrances is shown in Fig.2, where two external current sources at two entrances with their entrance AADT count values respectively, and each branch has two equal resistances with a value of its half road length and a sink current source located at its middle point with its value determined by three different design circuit models as described below.

3.B. Three Circuit Models

We design three different models (as sub-models) denoted as M_{11}, M_{12} and M_{13} by considering traffic characteristics in statistical sense as follows.

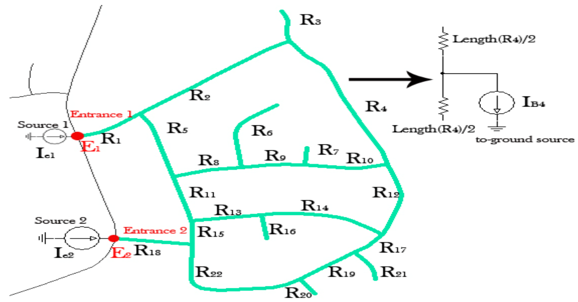

Fig. 2. Even distribution model – an illustration for conversion from a real community map in GIS to a circuit network

(1) Even distribution (ED) model M_{11}

This model is to evenly distribute the total entrance AADT of this community network to each household that makes the i-th branch sink current source I_{Bi} as

$$I_{Bi} = I_o \cdot H_{Bi}/H_o , \quad i = 1, 2, 3, \dots, n \tag{2}$$

where H_{Bi} is the household number along the i-th road, H_o is the overall household number in the community, I_o is the overall/total entrance current source value, i.e., the sum of all entrance AADT counts in this community, and n is the total road/branch number in the community.

This model M_{11} reflects the characteristics that each household has an even contribution to the community AADT based on the total entrance AADT in statistical sense.

(2) Local distribution (LD) model M_{12}

We first divide the network into m divisions corresponding to m entrances of this network respectively, such that each division has its corresponding nearest entrance. The Dijkstra's algorithm [13] is used to calculate the distance of each point at the network to each entrance, and to divide the network into m divisions by our developed algorithm.

This local distribution model M_{12} is to locally and evenly distribute each entrance AADT traffic count only to the households within its corresponding division which has this entrance as the nearest entrance. Figure 3 shows an example, where the network has two entrances and is divided into two divisions as marked with two different colors respectively. Each branch sink current source value I_{Bi} is a distribution of its nearest entrance AADT count I_{ej} to this branch in the division as

$$I_{Bi} = I_{ej} \cdot H_{Bi}/H_{oj}, \quad i = 1, 2, 3 \dots, n_j, \;\; j = 1, \cdots, m \tag{3}$$

where H_{Bi} is the household number along the i-th road/branch, H_{oj} is the overall household number in the j-th division, I_{ej} is the j-th entrance current source value, i.e., the j-th entrance AADT count, n_j is the total road/branch number in the j-th division, and m is the total entrance number. Some branch may be divided into two sub-branches, i.e., it belongs two divisions as shown by two different colors in Fig. 3. We have developed the programs automatically to make divisions based on the above described rules and the traffic network in the GIS system.

This LD model M_{12} reflects the characteristics that each household usually drives through the nearest entrance to connect external traffic network, i.e., people usually drives by taking the shortest route. However, households are distributed along the branch. The branch (or sub-branch) sink current source reflects a statistical average along this branch (or sub-branch).

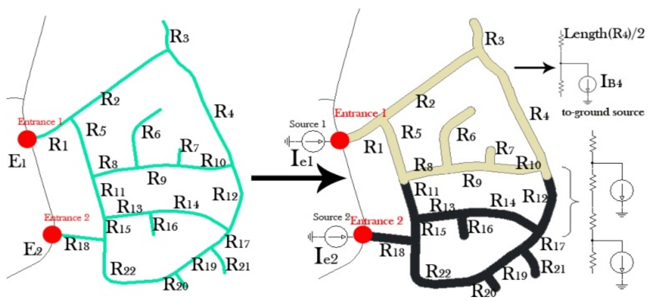

Fig.3. Local distribution model with two entrances

(3) Separate distribution (SD) model M_{13}

As mentioned above, the AADT and VMT on a road are counted without distinction of driving directions, but with combination of both direction counts. This fact is that unlike the electrical currents, the traffic flows from opposite directions cannot cancel each other. Then, for each branch, we need to add together the absolute current values on this branch generated by every individual entrance current source respectively. Based on this observation, we develop a separate distribution (SD) model M_{13}, in which we separate the entrance current sources from each other, i.e., we let only one entrance current source affect on the whole network at one time, then one by one.

It needs to run simulations for each entrance current source I_{ej} individually. Thus, the model runs m separate individual simulations with only one entrance current source at each time. It seems to apply "superposition" theorem here. However, the model M_{13} is not using superposition principle here because we take *absolute value summation* of individual simulation outcome on the same branch. That is totally different from the superposition principle which takes the *algebraic summation* of individual outcomes and leads to the result as the model M_{11}. Model M_{13} is to evenly distribute each entrance traffic count AADT I_{ej} to each household in the community.

This treatment makes model M_{13} to reflect the characteristics that the AADT and VMT on a road are counted in summing traffic flows of two-way directions on this road as defined.

As described above, there is only one entrance current source at one entrance at a time in each simulation. At that time, the other entrances should be open, no current sources connected to. In real circuit simulation, we connect sufficient large resistors ("infinite") to these respective entrances and the ground.

Each branch sink current source needs to be calculated based on each individual entrance current source (i.e., its entrance AADT count) separately in each simulation run. At the j-th run with the j-th entrance current source I_{ej}, the i-th branch sink current source I_{Bij} is

$$I_{Bij} = I_{ej} \cdot H_{Bi}/H_o, i = 1, 2, 3, \ldots, n, \quad j = 1, \cdots, m \quad (4)$$

where H_{Bi} is the household number along the i-th road/branch, H_o is the overall household number in the community, and n is the total road/branch number in the community.

Fig. 4 shows an example of this model M_{13} with two entrances and two simulation runs.

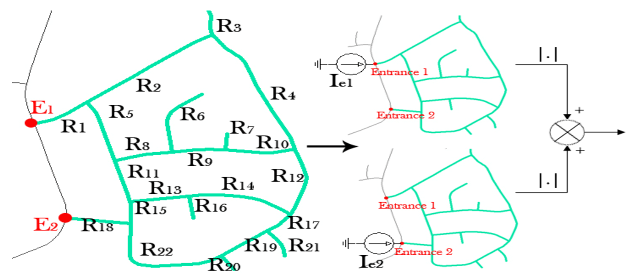

Fig.4. Separate distribution model

Notice that in each simulation run, the branch sink current sources need to be calculated as (4) based on distinct entrance current source I_{ej}. It is further noticed that the number of branches is usually much greater than the number of entrances in a community, i.e., $n \gg m$. Thus, we further develop a new simulation process for model M_{13} to make it more efficient as follows. We let the branch sink current sources be calculated by only one time based on a predetermined entrance current amount I_p, say 1,000. Then at each run time the entrance current source value is fixed as I_p, and each simulation result on each branch is adjusted by timing a ratio I_{ej}/I_p before taking their absolute value summation. It makes our automatic program and simulation much easier and more efficiency. This new treatment is as shown in Fig.5 instead of Fig.4.

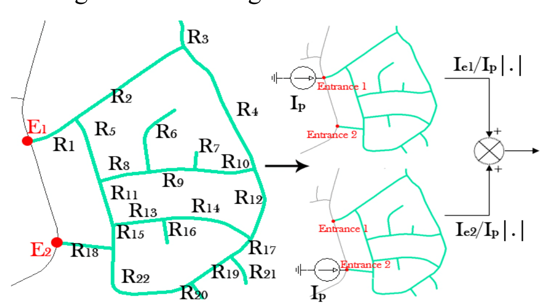

Fig.5. A modified simulation method for separate distribution model

3.C. *Combination Model M_1 and Least Square Method*

Based on the models ED, LD and SD, i.e., M_{11}, M_{12} and M_{13}, we further develop a combination model M_1 by the

Least Squares Method (LSM) to effectively estimate and predict the AADT and VMT on community networks. Therefore, the above three models are sub-models for the combination model M_1. We apply the LSM to get the optimal model M_1 in the sense of minimizing the sum of error squares between the observed AADT and the simulated AADT on all observed sample roads. Let total observed k sample road points be $p_1, p_2, \cdots, p_k$ in selected different communities, and $\hat{y}_i$ be the estimated AADT at point $p_i, i = 1, \cdots, k$, respectively. As an optimal estimation, we let it be an orthogonal projection of the accurate value onto our modeling space spanned by the above three models. We set the model M_1 as an optimal linear combination of models M_{11}, M_{12} and M_{13}. It leads to

$$\hat{y} = w_e \cdot y_e + w_l \cdot y_l + w_s \cdot y_s \quad (5)$$

where $\hat{y}$ is the AADT estimate of model M_1, w_e, w_l and w_s are the weights for the AADT estimate outcomes y_e, y_l and y_s of the ED, LD and SD models (M_{11}, M_{12} and M_{13}), respectively. Thus, the estimated/predicted AADT $\hat{y}$ at each measurement road point p_i is $\hat{y}_i$ as

$$\hat{y}_i = w_e \cdot y_{ie} + w_l \cdot y_{il} + w_s \cdot y_{is}, \; i = 1,2, \cdots, k \quad (6)$$

where y_{ie}, y_{il} and y_{is} are the outcomes of the M_{11}, M_{12} and M_{13} at the point p_i, respectively. To find the optimal weighting vector $w = [w_e, w_l, w_s]^T$, we apply the LMS to the measured data $y = [y_1 \quad y_2 \quad \cdots \quad y_k]^T$ from the counts, and the predicted data M from the simulations of models M_{11}, M_{12} and M_{13} as

$$M = \begin{bmatrix} y_{1e} & y_{1l} & y_{1s} \\ y_{2e} & y_{2l} & y_{2s} \\ \vdots & \vdots & \vdots \\ y_{ke} & y_{kl} & y_{ks} \end{bmatrix} \quad (7)$$

By the LSM, we have the optimal weighting vector

$$w = (M^T M)^{-1} M^T y \quad (8)$$

It leads to our optimal estimate/prediction AADT values as the estimate vector $\hat{y}$ as in (5) as

$$\hat{y} = [y_e, \; y_l, \; y_s] \cdot w \quad (9)$$

Please note that we may apply the data of only observed internal points in communities in (6)-(9), or the data of all observed points in communities, i.e., including the measured entrance points if available.

Furthermore, when the weighting vector w is derived via the LSM, we can apply it to all roads in the community network by using the simulation results from models M_{11}, M_{12} and M_{13} in (9), i.e., to make the AADT estimate/prediction on every road of the community network by the combination model M_1 via the circuit network approach. For the VMT estimation and prediction, we can just make a multiplication of the estimated AADT and its road length first (i.e., the voltage in the circuit network), and then sum each road VMT (voltage) for the area VMT. It can be used for calculating the citywide and statewide VMT estimation and prediction.

3.D. Circuit Network and Its Simulation

Based on the above proposed models, the simulations are via the circuit network. We have developed the software to automatically generate the above described three circuit networks of models M_{11}, M_{12} and M_{13} directly from the traffic road network in the GIS. After that, the circuit networks are simulated by the common circuit software Spice or PSpice [14]. Finally, our software outputs the results of model M_1 based on the circuit network simulation and the LSM algorithm.

Furthermore, we may use the new method to estimate the AADT and VMT on community local area roads even without any traffic measurement for other similar communities. It is because we may use the total household number to calculate the total entrance traffic amount for our modeling with minor modification.

IV. Experiments and Analysis

In this section, we describe our experiments and analysis. We take experiments on our presented models and simulation via the above approach and methods.

We select eight communities in Mecklenburg county and divide them into two groups based on the respective total household number in each community. Group 1 has four communities (C1 – C4) with each total household number less than or equal to 200; while Group 2 also has four communities (C5 – C8) with each total household number greater than 200. Table I lists the total household number, sum of observed entrance AADT, number of entrances, number of observed internal points, and number of overall observed points of each community.

Our developed program can automatically convert each community network in the ArcGIS to the circuit network in PSpice as the ED, LD and SD models (M_{11}, M_{12} and M_{13}) respectively, and run their simulations by the PSpice. Finally the AADT estimations on all roads in the network are obtained via (7)-(9) of M_1.

The traffic amounts at entrances and internal sample points of these tested communities are measured as described in section II and converted to the AADTs for tests.

TABLE I. Two Test Groups and Their information

Community	Number of House-holds	Sum of Observed Entrance AADT	Number of Entrance Points	Number of Observed Internal Points	Number of Overall Observed Points
Total	2,820	28,977	20	27	47
Group 1	496	5,413	8	11	19
C1	107	709	2	2	4
C2	125	1,040	2	2	4
C3	171	2,104	2	3	5
C4	200	2,269	2	4	6
Group 2	2,324	23,564	12	16	28
C5	482	4,756	3	2	5
C6	493	5,157	3	3	6
C7	501	4,731	3	3	6
C8	848	8,920	3	8	11

Currently, the methods in practice [1, 5, 9] calculate the mean AADT of group samples, and then apply it to all roads in the group. Thus, for comparison we check the relative errors between the predicted and observed average AADT from all k sample points in each group for accuracy evaluation. Two types of averages are used. One is the simple arithmetic average, i.e., the mean as usual. Another one is the weighted average as

$$weighted\ average\ AADT = \left(\sum_{i=1}^{k} l_i \cdot \hat{y}_i\right) / \sum_{i=1}^{k} l_i \quad (10)$$

where l_i is the length of test road i. The observed weighted average AADT is calculated similarly to (10) by using the measurement y_i to substitute the estimate $\hat{y}_i$. We also check on two kinds of test sample points: one includes only all internal sample points, and another includes all observed sample points of both entrance points and internal points.

Table II lists the experiment results from the model M_1, the simulations by the PSpice, and the measurements. The experiments show the relative errors of the predicted mean AADT at all observed sample points ranging from 0.93% to 2.51%, and at all internal sample points ranging from 2.25% to 8.48%.

The experiments show that the presented new models via the circuit approach are valid with high accuracy in statistical sense. Due to page limit, we omit VMT results for networks. However, the relative error of the weighted mean AADT reflects the estimated VMT accuracy on the sampled roads.

V. Conclusions

In this paper, we propose new circuit models for community AADT &VMT estimation and prediction. It provides an approach, i.e., via the circuit network models and simulation, to solve a long-time existing problem for the AADT and VMT estimate on the community traffic networks, where it is usually lack of the traffic monitoring system. The experiment results show that the approach, models and methods are valid and successful. It presents a high accurate estimation capability. The approach can be applied and extended to the AADT and VMT estimation and prediction on local road networks with the advantages of labor saving, the GIS compatibility, and automation.

This presented novel approach and methods are the first time to estimate the AADT and VMT by the circuit network for the traffic network in the literature. It is also discovered that the total entrance traffic amount is strongly related to the total number of households in communities. Thus, as mentioned above, it makes the new methods feasible to estimate the AADT and VMT on community local area roads even without any traffic measurement for other similar communities. We will present it in another paper in future in view of the page limit here.

TABLE II. Predicted AADT and Relative Error for Two Groups

Checking Points	Group	Observed Mean AADT	M_1—Mean AADT	Relative Error	Obs. Weighted Mean AADT	M_1— Weighted Mean AADT	Relative Error
All points	G1	457.32	445.85	2.51%	352.06	339.74	3.50%
	G2	1439.14	1425.7	0.93%	1544.62	1462.13	5.34%
	Total	1042.23	1029.59	1.21%	951.4	903.81	5.00%
Internal Points Only	G1	233.36	213.57	8.48%	207.13	188.53	8.98%
	G2	1045.75	1022.23	2.25%	1277.5	1143.61	10.48%
	Total	714.78	692.77	3.08%	725.73	651.27	10.26%

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