Netw Spat Econ
DOI 10.1007/s11067-017-9341-6

Modeling Vehicle Miles Traveled on Local Roads Using Classification Roadway Spatial Structure

Xiubin B. Wang[1] · **Xiaowei Cao**[1] · **Kai Yin**[2] · **Teresa M. Adams**[3]

Abstract This paper models the relationship between vehicle miles traveled (VMT) on local and collector roads with an objective to predict local road VMT by using collector road VMT. Through a continuous approximation method typically used for vehicle routing, it first analytically reveals this relationship mainly as a function of roadway density ratios between multiple roadway classifications. This structural relationship suggests regression equations using density ratios or logarithmic values of them as the explanatory variables. The use of regression equations enables to account for varying spatial distributions of roadways and demand through parameter calibration. The proposed regression equations are proved good fits through computer simulation using distinct community road network topologies. In addition, practical data from Hennepin County of Minnesota, U.S.A. that encompasses Minneapolis indicates that our developed regression equations can work well.

Keywords Vehicle miles traveled · Roadway classification

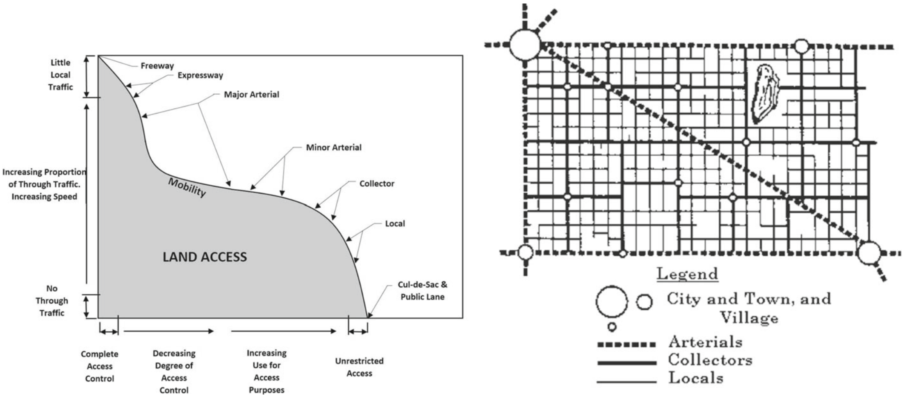
✉ Xiubin B. Wang
bwang@tamu.edu; xbwang@gmail.com

1 Zachry Department of Civil Engineering, Texas A&M University, CEOB Building, 301F, Spence St., College Station, TX 77843, USA

2 HomeAway, Inc., 11800 Domain Blvd #300, Austin, TX 78758, USA

3 Department of Civil and Environmental Engineering, University of Wisconsin – Madison, Madison, WI 53706, USA

Published online: 27 February 2017



(a) (b)

Fig. 1 (**a**) Accessibility vs. mobility of the U.S. road classification system (Source: FHWA, 1992); (**b**) Hierarchical structure of the U.S. road system (Source: Hausman, 2011)

1 Background

Vehicle miles traveled (VMT) refers to the total miles traveled by vehicles on the roadway. The Federal Department of Transportation requires that each state report the VMT according to the roadway functional classification, which includes local, collector, minor arterial, and principal arterial roads (FHWA 2013). Local streets are generally the community roads that provide access to properties, and are formally defined as those not included in any other functional classifications in rural or urban areas. According to the 2000 U.S. data, the principal arterial plus minor arterial street system, the collector street system and the local street system accounted respectively for 15–25, 5–10 and 65–80 % of the total road miles and 65–80, 5–10 and 10–30 % VMT nationwide, respectively (FHWA, 2013). The primary function of road classes varies from providing accessibility to mobility. Figure 1a illustrates a transition from accessibility to mobility as travelers move from local streets onto arterial roads, Fig. 1b shows an example neighborhood roadway network with hierarchical roads designed to serve a combination of functions between accessibility and mobility. Interested readers may refer to Levinson and Zhu (2012), which provides detailed description of the origin, purposes, governance and VMT shares of the hierarchical road system, an excellent background for this work. The hierarchical roadway system, whose road density sharply decreases as the road class goes from local, collector to arterial roads, is often featured in scientific studies such as in Chapter 4 of Newell (1980).

The VMT for each roadway classification is an indicator of roadway usage. Therefore, the Federal Department of Transportation by law generally allocates apportionment fund to each state under different systems such as the National Highway System (NHS) and the Interstate Maintenance System (IMS) based on the ratio of the total VMT traveled on a state's public roads to the national total on the same functional class of roads (Fricker and Kumapley 2002). The apportionment fund is a multi-billion dollar budget each year. Accurate report to the federal Department of Transportation about the VMT estimates means accurate implementation of federal law. In addition, accurate VMT numbers provide a sound basis for analysis of gas consumption and environmental impact. A major challenge in the VMT report system has been with the local road VMT estimation for which no established method is available yet to our best knowledge.

State departments of transportation (DOTs) and local transportation agencies traditionally resort to traffic count programs to get the traffic count data for VMT estimation. These traffic count programs well cover higher classes of roads, primarily arterial roads by using permanent count stations. FHWA's Highway Performance Monitoring System (HPMS) (FHWA, 2013) provides detailed guidelines as to data collection and calculation of VMT on higher classifications of roads. In particular, freeways have traffic data from continuous monitoring so that the VMT calculations are generally considered accurate and reliable. However, traffic counts on local roads are not practical and are usually not available. HPMS does not specify any specific sampling method for local road traffic counts. Determining the methods for estimating local road VMT is generally left to each state DOT.

The primary difficulty of estimating local road VMT is the lack of sufficient traffic data. Data collection on local roads proves challenging and costly, and is especially so when no proper and effective sampling method is developed. The low traffic density and pervasiveness of local roads make it impossible to count traffic in a similar way as for the arterial or collector roads. Among the better methods for estimating local road VMT is using traffic counts conducted on sampled sections of local roads such as Frawley (2002), which requires traffic count samples every year on local roads but is not able to provide error analysis. In this paper, we make an effort to develop an alternative method to avoid the costly undertaking of sampling traffic count every year. We believe that local road VMT must have a close relationship to higher classification road VMT. Therefore, we choose to use classification roadway spacing and higher class road VMT estimates for the estimation. Under this method, only calibration of the regression equations once every few years through survey would generally be needed. In particular, by following the general continuous approximation concept for vehicle routing, we first analytically develop a structural relationship of VMT between local and collector roads in terms of classification road densities under restrictive assumptions. The structural relationship reveals key explanatory variables and allows to propose sound regression equations using these explanatory variables, calibration of which by using field data would account for noises due to defiance of the assumptions. The regression equations can be relatively easily calibrated. As will be seen, the ease of application of our proposed method presents a compelling advantage. An application is found to fit well in Minneapolis area of Hennepin County, Minnesota, one of the largest urban areas in the U.S.

2 Literature on VMT Estimation

Due to the practical need, there has been a long effort in developing methods for the VMT estimation. The methodologies generally fall into three categories: traffic-count based, non-traffic-count based, and local road specific methods. Both Qian (2013) and Kumapley and Fricker (1996) present a review of the relevant literature.

The traffic count method first obtains the 24-hr traffic counts on a sampled section multiplied by its centerline mileage to estimate the VMT for this section. Subsequently, the value is annualized by multiplying it by the number of days in a year. It assumes that the actual mileage of roads is known. The accuracy of traffic-count based VMT estimates is determined by the accuracy of traffic data used for the estimation (FHWA, 2013). This method is specified in the HPMS guideline mainly for arterial roads, and is the most accepted method in the United States. If the sampling procedure is appropriate, the estimates derived would be accurate. This method applies well to the higher classes of roads, which is not nearly as pervasive as the local roads. Building on the traffic count, Qian (2013) utilizes a scale-free property in a network, which gives rise to a power-law model using logarithmic terms of VMT.

Non-traffic-count-based VMT estimation methods estimate VMT by using non-traffic data, such as socioeconomic data including trip-making behavior, household size, household income, population, number of licensed drivers, employment and fuel sales (Fricker and Kumapley 2002; Oakridge National Laboratory 2011; Retziou et al. 2012; Stone et al. 2005, for example). However, most of these socioeconomic data are difficult and costly to collect on a yearly basis. The Nationwide Personal Transportation Survey is often the source of data (Stone et al. 2005), although not updated every year.

To directly overcome the lack of traffic count on the local road, Zhong and Hanson (2009) use travel demand models (TDM), specifically traffic assignment method, to estimate traffic volumes on lower class roads. But the undertaking is daunting and appears hard for general implementation. Alternatively, Seaver et al. (2000) use county level demographic data from Census for regression to predict local road average daily traffic. One issue of it is the lagging update of Census data. Frawley (2002) proposes a simple random sample method to randomly collect 24-hour traffic count data on select local road stations in order to estimate local road VMT. All these methods demand intensive traffic data for sampled local roads, and yet no analysis of estimation errors is provided. In addition, sampling every year on large scale local roads is costly. The research question in this paper is: can one predict local road VMT by using collector road VMT along with easily available data such as road density? This implies an alternative way for local VMT estimation.

Beyond the practical norm, an inherently connected but rarely noticed literature is the continuous approximation for the traveling salesman problem (TSP), which is primarily intended for finding the shortest travel distance of serving a set of customer locations within an area, assuming that customers are uniformly distributed and follow Euclidean distances between locations. Typically, the distance of travel is found to be a function of service area and demand density such as approximated by $\phi\sqrt{AN}$ when N tends to be large, where ϕ is a constant to be calibrated, A the area of service, and N the number of customers (Christofides et al. 1971; Daganzo 1984).

There are a few papers in the literature that use continuous approximation for travel distances and flows over city networks with idealized shapes (Holroyd 1966; Miller 1967; Smeed 1970) and study effects of high-speed ring roads (Pearce 1974), most of which serve for the transportation planning processes (Saidi et al. 2016).

Worthy of a special mention, chapter 4 of a monograph (Newell 1980) studies travel distance on several idealized networks such as rectangular, triangular grids of roads, and radial-ring networks, using approximation to the local roads when the hierarchical road networks also consist of a fast road.

Several other relevant literature are in social sciences studies, which relates network structure such as road spacing and population density with the total trip distance, implying that network route behavior to a great extent depends on the network spatial structure (Parthasarathi et al. 2012, 2015). One issue is about proposing explanatory variables, which often lacks analytical support. In comparison, our work here specifically addresses the VMT prediction only for local roads not for the total mileage of several classifications. Our method starts with analytical derivation for the explanatory terms by resorting to the continuous approximation method.

A major advantage from using continuous approximation, the resulting formulas are simple for application: minimal input information is needed. The input are generally macroscopic data such as road density. This paper makes an effort to characterize the local road VMT as a function of road and demand spatial characteristics. Analytical formulas are first established for quantifying local road VMT relative to the collector road VMT. The local road VMT estimation problem here is no less complex than the traditional continuous approximation. However, the actual spatial structure of roads and demand distribution show large variation that defies the uniform assumptions about road spacing and demand locations based on which the rigorous analytical formulas are derived, and challenges the validity of direct use of the derived analytical formulas. We therefore subsequently propose regression equations by using key terms from the analytical formulas as the explanatory variables to allow for noises due to deviation from the idealistic assumptions. The primary explanatory terms as identified in the analytical formulas are the road density ratios between classifications. Without these analytical results, it would be hardly possible to identify road density ratios as the explanatory variables for VMT estimation. Deviation from the restrictive assumptions is accounted for through calibrating the coefficients with field data. In validation of our developed models, a formula calibrated through simulation applies well to the urban area of Minneapolis in Minnesota, U.S.A.

3 Modeling Local Road VMT Estimation

For modeling, we assume a typical road structure as in Fig. 2a, in which the most sparse grid network, the first layer, is for the principal arterial road. Within each grid of the principal arterial, the second layer, is a grid network of minor arterial roads, which is nested with grids of collector and local roads in sequence. The most dense is the local road. A representative trip leaves a neighborhood, traverses local roads, gets to the closest collector road, heads to the minor arterial road before traveling on the principal arterial towards its destination. Approaching destination is a reverse process of the starting in terms of the sequence of class roads. Therefore, we only examine the miles traveled on local and collector roads at the start of trips, implying that a similar relationship retains at the end of the trip.

The following notations are used in this paper.

Notations

s_L	spacing between parallel local roads
s_C	spacing between parallel collector roads
s_M	spacing between parallel minor arterial roads
s_P	spacing between parallel principal arterial roads
Q_L	local road VMT
Q_C	collector road VMT
Q_M	minor arterial road VMT
d_L	average local distance traveled
d_C	average collector road distance traveled
d_A	average principal arterial road distance traveled
ρ_L	local road density, which is local road mileage divided by the according area served
ρ_C	collector road density, which is collector road mileage divided by the according served area
ρ_M	minor arterial road density, which is minor arterial road length divided by the served area
ρ_P	principal arterial road density, which is principal arterial road length divided by the served area
v_A	speed on the arterial road
v_C	speed on the collector road
v_L	speed on local road

In the notations above, the subscripts L, C, M, P are for local, collector, minor arterial, and principal arterial roads, respectively. When the minor and principal arterial roads are not differentiated, we simply use the subscript A.

3.1 Local and Collector Road VMT Calculation

We first consider a local community in rectangular shape as in Fig. 2b, within which only local roads are available. The rectangle has a size L by W whose outer edge is the collector road. We further suppose that $W = \epsilon L$ where $\epsilon \in (0, 1]$. A special case of it is a square when $\epsilon = 1$. Note that we use the terms neighborhood and local community interchangeably later. An assumption is $v_A >> v_C >> v_L$ in the derivation, which dictates travelers to get to the closest collector road first in their itinerary. In Section 3.1.1, a discussion is conducted that relaxes this speed requirement.

In the neighborhood as described in Fig. 2b, commuters are assumed to be uniformly distributed, each having the same chance of destining to each of the four directions. We further assume that each commuter starts out on local road first heading for the nearest collector road, which is the edge of the rectangle, along which to get to the closest corner in the direction of the trip destination until the commuter leaves the neighborhood. For example, Fig. 2a shows a trip in red through

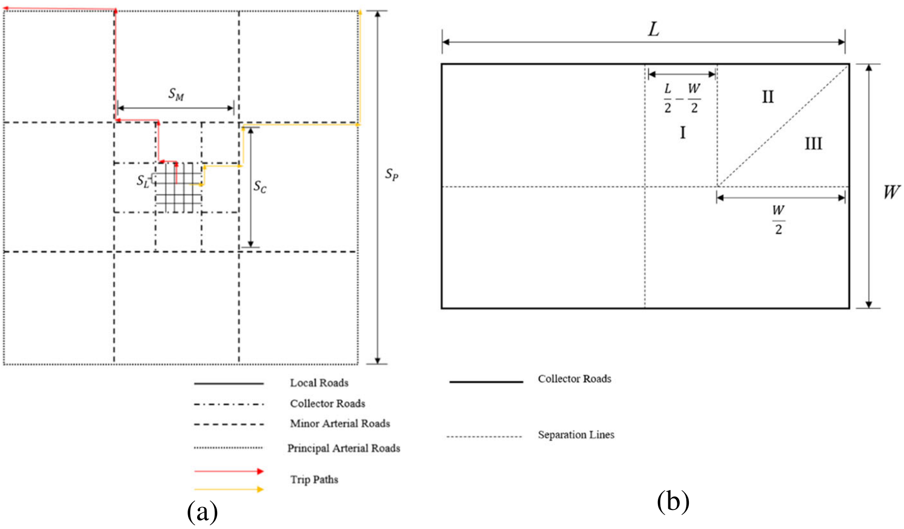


Fig. 2 (**a**) Illustrative network layout and example trip itineraries, (**b**) A representative local community (Better illustrated through color graph in electronic form)

the northwest corner that is destined to the north or west. Note that an earlier use of the network as Fig. 2 is seen in Section 4.1 of Newell (1980), which characterizes the local road network as one with arbitrarily fine grid network of local roads superimposed with sparse collector roads.

Take the first quadrant of the rectangle in Fig. 2b for calculating average local distance per traveler. The other three quadrants are images of this one. The first quadrant has three sections as follows.

Section I: A rectangle $(\frac{L}{2} - \frac{W}{2}) \times \frac{W}{2}$, in which travelers go up along local roads to get to the collector road.
Section II: A right triangle of $\frac{W}{2} \times \frac{W}{2}$, in which travelers also go up to the collector road first.
Section III: A right triangle of $\frac{W}{2} \times \frac{W}{2}$, in which travelers go right to collector road first.

Without considering spacing of local roads, which means all local travels immediately get to a local road of intended direction right away, Section I has an average local distance traveled $\frac{W}{4}$. Sections II and III each have an average local distance traveled as follows.

$$\frac{\int_0^{\frac{W}{2}} (\frac{w}{2} - x) \cdot x \cdot dx}{\frac{1}{2} \times \frac{W}{2} \times \frac{W}{2}} = \frac{W}{6}. \tag{1}$$

Therefore, the average local distance for the entire first quadrant is as follows:

$$\begin{aligned}
&\frac{\frac{W}{4} \times \frac{L-W}{2} \times \frac{W}{2} + \frac{W}{6} \times \frac{W^2}{4}}{\frac{LW}{4}} \\
&= \frac{W}{4}(1 - \frac{W}{3L}) \\
&= \frac{(3-\epsilon)\epsilon}{12} L. \qquad (2)
\end{aligned}$$

If s_L is used to denote the spacing between parallel local roads, assuming equal spacing of roads in EW and SN directions, the average travel distance of trips within the three sections is as follows.

$$d_L = \frac{(3-\epsilon)\epsilon}{12} L + \frac{s_L}{4}. \qquad (3)$$

We next discuss the collector and minor arterial road densities. Take collector roads as an example. A grid network of collector roads has m horizontal lines with a distance W apart and m vertical lines with a distance L apart. The total collector road mileage is $m^2(L+W)$ while the total area for this road mileage is $m^2 LW$. Therefore, the collector road density, denoted by ρ_C can be expressed as $\rho_C = \frac{L+W}{LW} = \frac{\epsilon+1}{\epsilon L}$. Similarly, the minor arterial road density can be expressed as $\rho_M = \frac{\gamma+1}{\gamma s_M}$, where s_M is the length of the rectangle surrounded by minor arterial roads and γs_M is the width of the minor arterial cell with $\gamma \in (0, 1]$. Note that a minor arterial cell is similar to that in Fig. 2b. However, the density of local roads ρ_L is still equal to $\frac{2}{s_L}$ according to the definition in the previous section, assuming local road spacing is uniform both horizontally and vertically.

Following a similar procedure to Eq. (3), the average distance traveled on collector roads, denoted by d_C, can be calculated.

$$\begin{aligned}
d_C &= \frac{(3-\gamma)\gamma}{12} s_M + \frac{\frac{W}{4} \times \frac{W^2}{4} + \frac{L+W}{4} \times \frac{L-W}{2} \times \frac{W}{2}}{\frac{LW}{4}} \\
&= \frac{(3-\gamma)\gamma}{12} s_M + \frac{1}{4} L. \qquad (4)
\end{aligned}$$

Assuming that demand is uniformly distributed in the community, the ratio between local road VMT and collector road VMT can be derived as follows.

$$\begin{aligned}
\frac{Q_L}{Q_C} &= \frac{\frac{(3-\epsilon)\epsilon}{12} L + \frac{1}{4} s_L}{\frac{(3-\gamma)\gamma}{12} s_M + \frac{1}{4} L} \\
&\approx \frac{\frac{(3-\epsilon)\epsilon}{12} L + \frac{1}{4} s_L}{\frac{(3-\gamma)\gamma}{12} s_M} \\
&= \frac{(3-\epsilon)(\epsilon+1)}{(3-\gamma)(\gamma+1)} \cdot \frac{\rho_M}{\rho_C} + \frac{6}{(3-\gamma)(\gamma+1)} \cdot \frac{\rho_M}{\rho_L}. \qquad (5)
\end{aligned}$$

Therefore, we propose the following general regression model between local and collector road VMTs as follows.

$$\frac{Q_L}{Q_C} = \alpha_1 \frac{\rho_M}{\rho_C} + \alpha_2 \frac{\rho_M}{\rho_L} + \alpha_0. \tag{6}$$

where α_i is the parameter to calibrate, and in particular, α_0 is introduced to be more capable of accommodating deviation from the idealistic assumption of road network. Equation (6) is intended for general practical applications.

As a special case, when the neighborhood is in a squared shape, the average local distance is $\frac{L}{6}$ in the case of zero local road spacing, and $\frac{L}{6} + \frac{s_L}{4}$ in the case of a local road spacing s_L. A traveler from the first quadrant of Fig. 2b has a choice to go either through the left or right street up to the closest (surrounding) collector road. As an example, consider a traveler in the first quadrant of the local community to go up to the north. We assume that traveler gets to the closer local street before going north to the collector road. This derivation implies that collector roads are much faster than local roads so that travelers always first attempt to get to the closest collector roads. The VMT ratio for square shaped neighborhood between local and collector roads, where $\epsilon = 1.0$, is reduced to the following as a special case of Eq. (5).

$$\frac{\rho_M}{\rho_C} + \frac{3}{2} \cdot \frac{\rho_M}{\rho_L}. \tag{7}$$

In Eqs. (5) and (7), a higher density for minor arterial roads ρ_M makes the collector VMT lower and therefore makes $\frac{Q_L}{Q_C}$ higher.

In particular, When collector road density $\rho_C \to \infty$, we have $\rho_C \to \rho_L$, which gives rise to $\frac{Q_L}{Q_C} = \frac{5}{2} \cdot \frac{\rho_M}{\rho_L}$; when $\rho_C \to 0$, then $\rho_C = \rho_M$, and the $\frac{Q_L}{Q_C} = 1 + \frac{3}{2} \cdot \frac{\rho_M}{\rho_L}$, provided that the nesting structure of the classification roads remains and that the area of community is limited. The reasonable range of ratio for the squared shape is $(\frac{5}{2} \cdot \frac{\rho_M}{\rho_L}, 1 + \frac{3}{2} \cdot \frac{\rho_M}{\rho_L})$.

In a similar fashion, one may propose a regression equation of similar format for the ratio $\frac{Q_C}{Q_M}$. This is done by reducing the roadway functional classes by one level Cao (2015): treating minor arterial and collector roads as collector and local roads, respectively.

Be aware that we are not particularly interested in determining a specific a priori value for the coefficient α in Eq. (6), but are interested in identifying the terms of $\frac{\rho_M}{\rho_C}$ and $\frac{\rho_M}{\rho_L}$ as key explanatory variables for the purpose of local road VMT estimation. We believe these terms are the determinants of the VMT ratios and that the coefficients of these terms, when Eq. (6) is applied, may be calibrated according to the actual road network spacing and trip distribution characteristics. The ultimate purpose is to apply these regression equations through field calibration.

3.1.1 Discussion: Local Roads as a Continuum

Section 4.3 of Newell (1980) characterizes the shortest path in a superposition of faster routes (e.g. collector roads) on two-dimensional continuum of slower roads. The shortest path always shows a pattern as indicated in Fig. 3, which features a maximum angle θ at which the shortest route enters the collector from the local road.

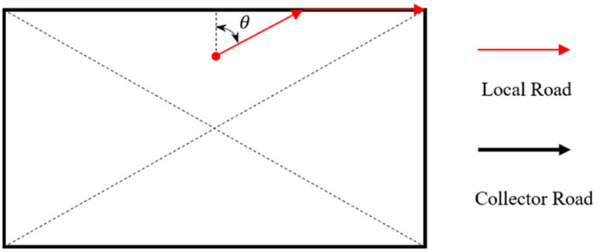


Fig. 3 Shortest path out of a continuum of local community. (Better illustrated in its electronic publication)

θ is determined by the relative speeds of v_L and v_C, $\cos\theta = 1 - \frac{v_L}{v_C}$. If the line connecting the trip origin to the destination (e.g. the upper-right corner) shows an entry angle smaller than θ, the shortest path falls on the direct line. Otherwise, the shortest path is shown as in Fig. 3.

We use a special case to illustrate that the format of the formula in Eq. (6) is a general one. In this special case, we assume $\theta = 45°$. Therefore, every trip origin in Section II of Fig. 2b enters the collector road at an angle $\theta = 45°$. In this case, the total local road VMT for trips in Section II may be calculated as follows.

$$\int_0^{\frac{L}{2}-\frac{W}{2}} \int_x^{\frac{W}{2}} \frac{y}{\cos\theta} dydx = \frac{W^3}{48\cos\theta}. \tag{8}$$

The total local distance for area III is identical to that of area II due to symmetry. The total local distance of area I of Fig. 2b is shown as follows.

$$\int_0^{\frac{W}{2}} \int_0^{\frac{W}{2}} \frac{y}{\cos\theta} dydx = \frac{W^2(\frac{L}{2} - \frac{W}{2})}{8\cos\theta}. \tag{9}$$

Therefore the average local distance per traveler is expressed as follows.

$$\begin{aligned} d_L &= \frac{\frac{W^3}{24\cos\theta} + \frac{W^2(L-W)}{16\cos\theta}}{\frac{WL}{4}} \\ &= \frac{W\epsilon}{6\cos\theta} + \frac{W(1-\epsilon)}{4\cos\theta} \\ &= \frac{W(3-\epsilon)}{12\cos\theta} \\ &= \frac{L\epsilon(3-\epsilon)}{12\cos\theta}. \end{aligned} \tag{10}$$

The reduced collector road VMT per traveler as compared to that in Fig. 2 is $\frac{L\epsilon(3-\epsilon)\tan\theta}{12}$, which is ignorable in the denominator of Eq. (5). Equation (10) also results when local roads in a grid local road network intersect with collector roads at an angle θ as illustrated in Figure 4.2 of Newell (1980). It leads to support of the use of the term $\frac{\rho_M}{\rho_C}$ in Eq. (5), although with a different coefficient. Equation (10) does not lead to the use of term $\frac{\rho_M}{\rho_L}$ because the continuum approximation does not assume local road spacing.

3.2 Conjecture of Alternative Log Terms for the VMT Ratios

In Eq. (6), the first term dominates the second, which means $\frac{Q_L}{Q_C} \approx \alpha_1 \frac{\rho_M}{\rho_C}$. Roughly, one may have a log equality as $ln(Q_L) = ln(Q_C) + ln\rho_M - ln\rho_C + \alpha$. In general, for the purpose of establishing a regression equation and abating noise effects due to uneven distribution of roadways and trips, a regression equation may be appropriate as $ln(Q_L) = \alpha_1 ln(Q_C) + \alpha_2 ln\rho_M + \alpha_3 ln\rho_C + \alpha_0$ with the coefficients α_0 through α_3 to be calibrated using field data. Therefore, by a slight 'abuse' through adding a few similar terms, we propose the following alternative to Eq. (6):

$$ln(Q_L) = \alpha_0 + \alpha_1 ln(Q_C) + \alpha_2 ln\rho_M + \alpha_3 ln\rho_C + \alpha_4 ln\rho_L. \tag{11}$$

Here α_i with $(i = 0, 1, 2, 3, 4)$ is coefficient to be calibrated. Therefore Eqs. (6) and (11) are two alternative regression equations to estimate local road VMT.

It is not difficult to propose a logarithmic term regression equation for collector road VMT estimation of a similar format, details of which are not presented here but are available in Cao (2015).

3.3 Robustness of Key Terms to Circular Local Community

Section 3.1 finds that road density ratio effectively explains the VMT ratio between road classifications under those particular assumptions. Would the same result hold when the shape of the local community drastically changes? In this subsection, we examine the local and collector road VMTs in an ideally circular-shaped community to verify that the density ratio terms are robust as explanatory variable. Suppose that the circular local community is surrounded by a collector road as illustrated in Fig. 4a and that circular communities form an area surrounded by circular minor arterial road as in Fig. 4b.

Consider a continuous case again, in which demand of trips are uniformly generated within the circular-shaped community. A trip generated at any location within it has an equal probability to go to each of the four directions. The trip leaves the community at one of the six 'outlets' at equal probability. Each trip follows the radius line (shortest possible local road) to the nearest collector road, after which it goes to the according outlet and continues on the collector road until it gets to the minor arterial road as shown in Fig. 4b.

The total local distance traveled by all travelers from within a circular community can be represented as follows.

$$\int_0^{2\pi} \int_0^{R_C} (R_C - r)\lambda r dr d\theta = \frac{\lambda \pi R_C^3}{3}. \tag{12}$$

where λ is a demand density constant, and R_C is the radius of the circular collector road. In Eq. (12), $R_C - r$ is the shortest local distance traversed to the nearest collector road on the ring, regardless of the final destination.

Equation (12) shows a total local distance that does not change with the directional distribution of trip destination. This is because the assumption of much faster collector roads than local roads makes travelers get to the collector road as soon as

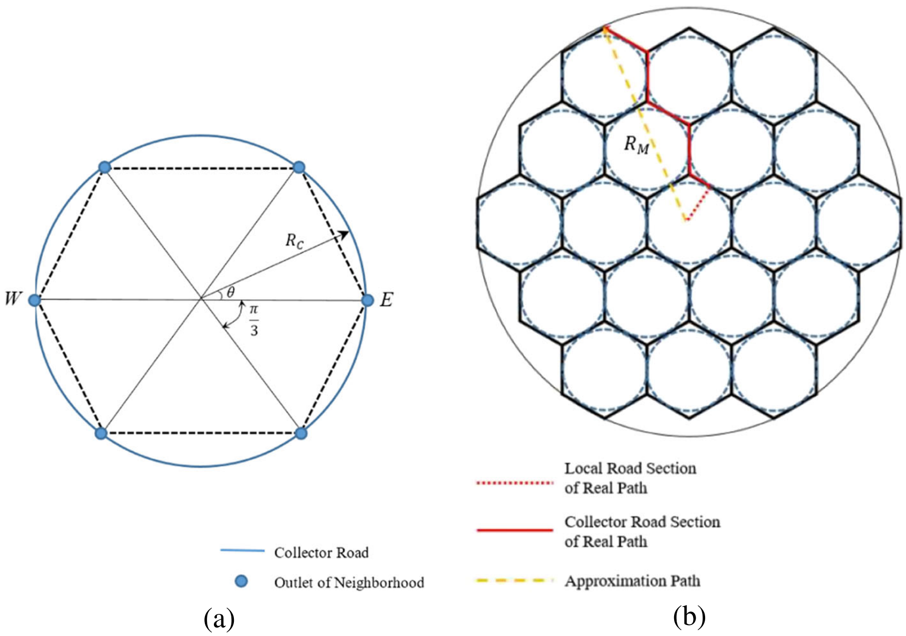


Fig. 4 (**a**) Circular local community surrounded by collector roads may be approximated by a hexagon; (**b**) *Large* hexagon (circle) contains *small* hexagons (circles). (Better illustrated through the color graph in its electronic publication)

possible regardless of the direction of the final destination, which means local travel always happens on the radius road towards the ring.

The total number of trips is

$$\int_0^{2\pi}\int_0^{R_C} \lambda r dr d\theta = \lambda\pi R_C^2. \tag{13}$$

Therefore, the average local distance traveled is $\frac{R_C}{3}$ by using Eqs. (12) and (13).

Now, we calculate the average collector VMT per trip on the ring of local community only while additional collector road VMT depends on the density of minor arterial roads. The total collector VMT on the ring of Fig. 4a is calculated as follows.

$$\begin{aligned}
&\int_0^{\frac{\pi}{3}}\int_0^{R_C} \frac{(\pi-\theta)R_C + (\frac{2\pi}{3}-\theta)R_C + (\frac{\pi}{3}-\theta)R_C + \theta R_C + (\frac{\pi}{3}+\theta)R_C + (\frac{2\pi}{3}+\theta)R_C}{6}\lambda r dr d\theta \\
&\quad = \int_0^{\frac{\pi}{3}}\int_0^{R_C} \frac{1}{2}\lambda\pi R_C r dr d\theta \\
&\quad = \frac{1}{12}\lambda\pi^2 R_C^3.
\end{aligned} \tag{14}$$

The six terms in the numerator of Eq. (14) are for collector road distance to the six outlets respectively. The denominator six means that each outlet has a chance of one sixth for a trip. The Eq. (14) is for $\theta \subset [0, \frac{\pi}{3}]$.

If the trips are uniformly generated in the six sectors of the circle as in Fig. 4a, all the six sectors are mirror images of each other in terms of trip patterns. Therefore, the total collector road distance on the ring of the circular community is $\frac{1}{2}\lambda\pi^2 R_C^3$.

Subsequently, the average collector road distance on the ring in Fig. 4a is calculated as follows:

$$\frac{\lambda\pi^2 R_C^3}{2\pi R_C^2 \lambda} = \frac{\pi}{2} R_C \tag{15}$$

Also, within or around a local neighborhood, the local and collector VMT per trip ratio becomes

$$\frac{Q_L}{Q_C} = \frac{\frac{R_C}{3}}{\frac{\pi R_C}{2}} = \frac{2}{3\pi} = constant \tag{16}$$

Next, in the same spirit, we consider the collector road distance traversed of a trip before reaching the minor arterial road. If minor arterial roads have a radius of R_M, the total collector road miles can be approximated by $\frac{\pi R_C}{2} + \frac{R_M}{3}$, assuming $R_M \gg R_C$, which means R_C is very small compared with R_M. Note that here $\frac{R_M}{3}$ is similar to the average local distance $\frac{R_C}{3}$ for a local community as calculated earlier.

Therefore, the ratio of local and collector road VMTs is equal to

$$\frac{Q_L}{Q_C} = \frac{\frac{R_C}{3}}{\frac{\pi R_C}{2} + \frac{R_M}{3}} \approx \frac{R_C}{R_M} \tag{17}$$

In this case, the collector road density ρ_C is calculated using half the circumference, assumed to be shared by circular areas at both sides of it, as follows:

$$\rho_C = \frac{\pi R_C}{\pi R_C^2} = \frac{1}{R_C} \tag{18}$$

The density for minor arterial can be obtained similarly: $\rho_M = \frac{1}{R_M}$, where R_M is the radius of minor arterial roads.

So, the ratio of local and collector road VMTs becomes

$$\frac{Q_L}{Q_C} \approx \frac{\rho_M}{\rho_C} \tag{19}$$

A polygon may practically approximate a circle well. Therefore, circular shapes may also be built to larger community of networks. The errors from using polygons to approximate circles are negligible relative to their magnitude. Figure 4b is an illustrative graph showing that a large hexagon comprises a large number of smaller hexagons that can be approximated by circles. The circles in dashed lines are the approximation to hexagons. The red line shows the path of an actual trip, which is approximated by the yellow line in our analysis.

Equation (19) indicates that the VMT ratio between collector and local roads can be effectively explained by a dominating term, the ratio between local and collector road densities. Equation (5) confirms the same dominating term. Therefore, our analysis of the circular shape reinforces the notion that road density ratio is a robust term in explaining the VMT ratio between roadway functional classes. Additionally, Eq. (19) supports using logarithmic terms to explain the VMT ratio.

We further find the following result based on circular shapes as in Figs. 4a and b.

Proposition 1 *As long as $R_M >> R_C$ and $v_A >> v_C >> v_L$, Equation* (19) *remains unchanged with any probability distribution of the trip destination out of the local community in* Fig. 4a.

We argue for Proposition 1 by assigning a probability distribution to the six outlets on the circle in Fig. 4a. Suppose there is a probability p_i of going to outlet i for a random traveler within the community, where $i \in \{1, 2, 3, 4, 5, 6\}$ and $\sum_i p_i = 1.0$. Suppose we index sequentially the outlets in the counter clockwise direction starting from the east most one.

The total collector road miles on the ring calculated in Eq. 14 for trips out of the first $\frac{\pi}{3}$ sector may be expressed as follows.

$$\int_0^{\frac{\pi}{3}} \int_0^{R_C} \Bigg((\pi - \theta) R_C p_1 + (\frac{2\pi}{3} - \theta) R_C p_2 + (\frac{\pi}{3} - \theta) R_C p_3 + \theta R_C p_4 + (\frac{\pi}{3} + \theta) R_C p_5 + (\frac{2\pi}{3} + \theta) R_C p_6 \Bigg) \lambda r dr d\theta. \tag{20}$$

For sector II through to IV, the according equations may be similarly presented as follows.

$$\int_0^{\frac{\pi}{3}} \int_0^{R_C} \Bigg((\pi - \theta) R_C p_2 + (\frac{2\pi}{3} - \theta) R_C p_3 + (\frac{\pi}{3} - \theta) R_C p_4 + \theta R_C p_5 + (\frac{\pi}{3} + \theta) R_C p_6 + (\frac{2\pi}{3} + \theta) R_C p_1 \Bigg) \lambda r dr d\theta. \tag{21}$$

......

$$\int_0^{\frac{\pi}{3}} \int_0^{R_C} \Bigg((\pi - \theta) R_C p_6 + (\frac{2\pi}{3} - \theta) R_C p_1 + (\frac{\pi}{3} - \theta) R_C p_2 + \theta R_C p_3 + (\frac{\pi}{3} + \theta) R_C p_4 + (\frac{2\pi}{3} + \theta) R_C p_5 \Bigg) \lambda r dr d\theta. \tag{22}$$

There are in total six equations from Eqs. (20) to (22). They are obtained by rotating the coordinate system counter-clock wise by an angle $\frac{\pi}{3}$ each time and rotate five times in sequence without changing the index of the six outlets. Note that rotating the coordinate system just makes the integration easier to present. Summing up all the above equations gives the same average collector road distance on the ring $\frac{\lambda \pi^2 R_C^3}{2}$ as before, which leads to Eq. (19).

In addition, the average collector road distance within the circular region of Fig. 4b, which is $\frac{R_M}{3}$, is a result of average radius distance when trips are all on the radius road to the nearest minor arterial road. This average $\frac{R_M}{3}$ has no variation with the locational distribution of the final destination of trips. In addition, the collector road distance on the ring of a circular local community as calculated in Eq. (15)

does not change with locational distribution of trip destinations, which is ignorable compared with the collector road traveled on the radius on the way to the (assumed) minor arterial ring. It is clear that the locational distribution of the trip destination, as in our assumption here, only affects the travel distance on major arterial roads, but does not affect the travel distance on collector roads. Therefore, using road density ratio to interpret the VMT ratio between collector and local roads is robust to the locational distribution of the trip destination in this restrictive case. In other words, Eq. (19) may be robust in practice, which supports use of this density ratio term in regression Eqs. (6) and (11).

4 Numerical Test of Local VMT Models

In ideal situations as assumed earlier for the derivation, Eq. (5) works. However, roadway layout and trip distribution often defy the assumptions. Therefore, our proposal is to use Eq. (6) and calibrate the coefficients with field data. The purpose of the analytical derivations is to identify key explanatory variables that effectively interpret the VMT on local roads.

Next, we show that the proposed regression equations work well in some realistic roadway situations.

4.1 Simulating Trips Out of Local Communities

In this test, we set up 35 different road patterns of local communities for simulation as partially illustrated in Fig. 5. Each community is a 8 by 8 units square surrounded by collector roads, and has a local road network within it. A complete list of the 35 patterns is seen in Cao (2015). The purpose is to use these 35 local road communities to test the effectiveness of Eqs. (6) and (11) via simulation. The 35 local communities are mainly based on Southworth and Ben-Joseph (2013). They represent dominating street design patterns in different time periods of history. As observed in Southworth and Ben-Joseph (2013), American conceptions of the residential street network have changed dramatically from the interconnected rectilinear grid pattern at the turn-of-the-century, to the fragmented grid and warped parallel streets of the 1930s and 1940s and the discontinuous, insular patterns of cul-de-sacs and loops that have been preferred since the 1950s. In managing the demand through our simulation, each local community is divided equally according to area into 64 squares, each square being referred to as a demand generator. The trip from each demand generator gets to the local road by following the shortest distance principle as in Fig. 6a. Local communities are lined in a 11 by 11 matrix surrounded by minor arterial roads as illustrated in Fig. 6b. More matrices of this may be arranged into a larger array to include higher classifications of roadway if needed. The speed on local, collector, and minor arterial roads are set to be 15, 40, and 60 units per unit time,respectively.

The simulation uses TransCAD as a tool for trip distribution and route choice. Trips, originated out of households, are assumed to be uniformly distributed within each local community. Again, each local community is equally divided into 64 trip generators. TransCAD treats trips out of each trip generator as all being originated

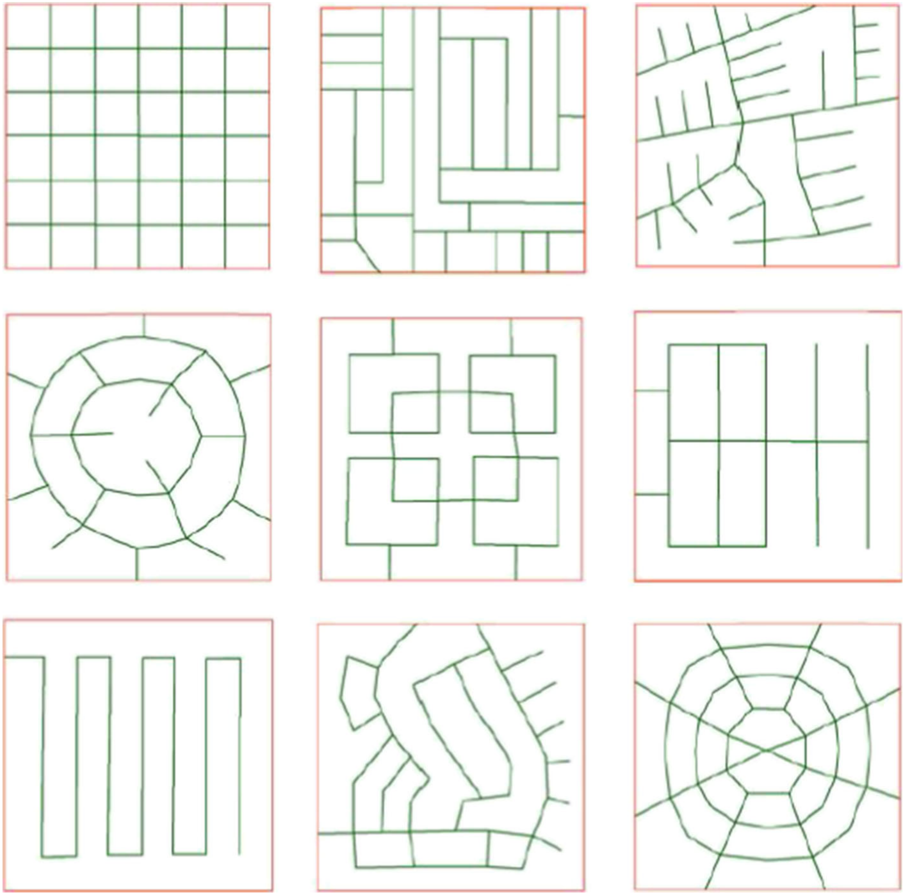


Fig. 5 Example local streets of 15 distinct local communities. (better illustrated in its electronic publication)

out of the center point of that generator square. TransCAD automatically connects each trip to the closest local road access point, then through a corner point of the local road to continue travel along local road onto collector road. Each trip is equally likely destined to one of the four corners of the large square formed by minor arterial roads as in Fig. 6b, assuming their final destinations are equally likely distributed in the four directions. In this way, all the local and collector road VMT at trip origins are simulated. VMT beyond the minor arterial roads are assumed to be on higher classes of roads (e.g. minor/principal arterial roads and freeways), and are not simulated and recorded in this work. This simulation is only about the distance at the origin on local and collector roads.

In Fig. 6a, the numbers on the red dotted lines are for traffic volumes. Each trip generator generates 10 units of trips, which sums up to 160 units of trips from each local community. These 160 units are equally likely distributed to the four corners

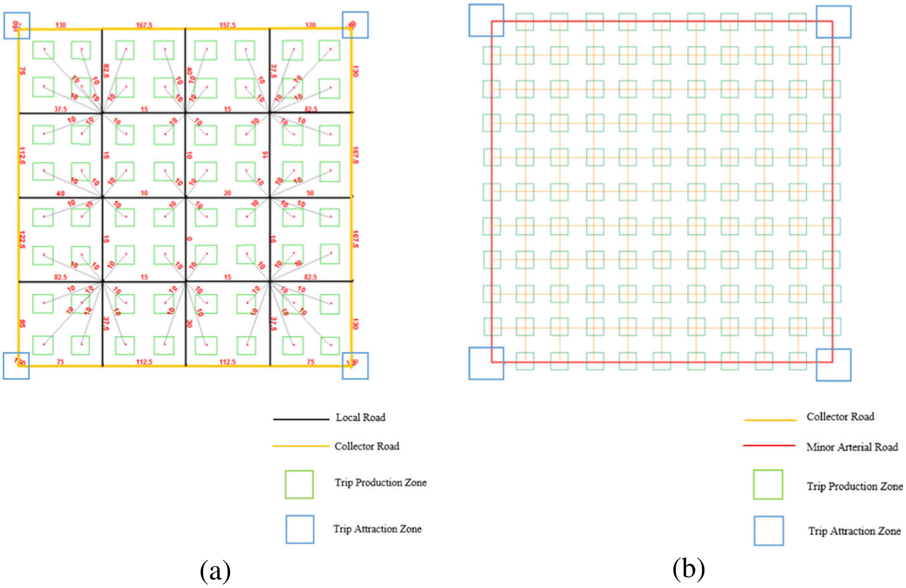


Fig. 6 (**a**) Local community with grid local road network for trip generation (legend of square shall change); (**b**) Grid network of hierarchical roads. (Better illustrated in its electronic publication)

of each local community, and continue to the four corners of the minor arterial road square at equal probability as in Fig. 6b.

At each run of the simulation, one of the 35 communities as Fig. 6a applies to form a road network as in Fig. 6b. The TransCAD simulation tracks the trajectory of each trip and records the VMT on local and collector roads respectively. In this simulation, the minor arterial roads have a spacing R_M, ten times the spacing of collector roads R_C, which roughly confirms the assumption that $R_M \gg R_C$. In this simulation network, there are $10 \times 10 = 100$ local communities separated by collector roads. Note that the primary purpose of this simulation is to test the fitness of the proposed regression equations.

Note that the road structure and spacing of the 35 community examples deviate from the idealistic at varying degrees. The degree to which a particular spacing defies the idealistic determines to a large extent how the coefficients deviate from the analytical ones as in Eq. (5). Network connectivity we believe is a good indicator of this deviation. The understanding here is that no single coefficient in Eq. (6) fits all situations of network connectivity, and that coefficients of Eq. (6) may be evaluated according to degree of network connectivity.

We adopt the popular β index to represent the road connectivity, which is defined below.

$$\beta = \frac{\text{Total number of Links}}{\text{Total number of Nodes}}. \tag{23}$$

β index is similarly proposed in Dill (2004) and is explained in Rodrigue et al. (2013). For interested readers, alternative measures are also discussed in Xie and Levinson (2007).

Table 1 Regression Equation of $\frac{Q_L}{Q_C}$

Regression Equation	β	R^2	Error (%)	Sample Size
$-5.93\frac{\rho_M}{\rho_C} + 42.58\frac{\rho_M}{\rho_L} - 0.07$	(0, 1.4]	0.20	71.92 %	10
$0.20\frac{\rho_M}{\rho_C} + 8.57\frac{\rho_M}{\rho_L} - 0.04$	(1.4, 2.0]	0.48	19.70 %	14
$0.28\frac{\rho_M}{\rho_C} + 2.50\frac{\rho_M}{\rho_L} + 0.02$	(2.0, ∞)	0.70	10.82 %	11

Note that the total number of links and nodes in Eq. (23) are for the total number within the area of modeling. Using the 35 example local communities, we subjectively classify the communities into three categories according to β: low connectivity with $\beta \in (0, 1.4]$, medium connectivity with $\beta \in (1.4, 2.0]$, high medium with $\beta \in (2.0, \infty)$. Accordingly the communities of simulation are clustered for respective regress analysis.

Equation (6) using the ratio method is calibrated and presented in Table 1. Table 1 also shows the respective R^2, relative regresion errors and the sample size. Here we measure the relative errors of the regression equations by using the formula $\frac{|Q_L - \widehat{Q_L}|}{Q_L}$, where Q_L is the actual local road VMT while $\widehat{Q_L}$ is the estimated local VMT using the according equation. The same notations of Q_L and $\widehat{Q_L}$ are also used in Tables 3 and 4 later. The average relative errors indicate that proposed explanatory variables apply well to the cases of medium to high network connectivity but not to the case of low connectivity. Note that this is based on identical weight to each of the 35 communities. Another drawback of our regression equation is that the sample size appears too small.

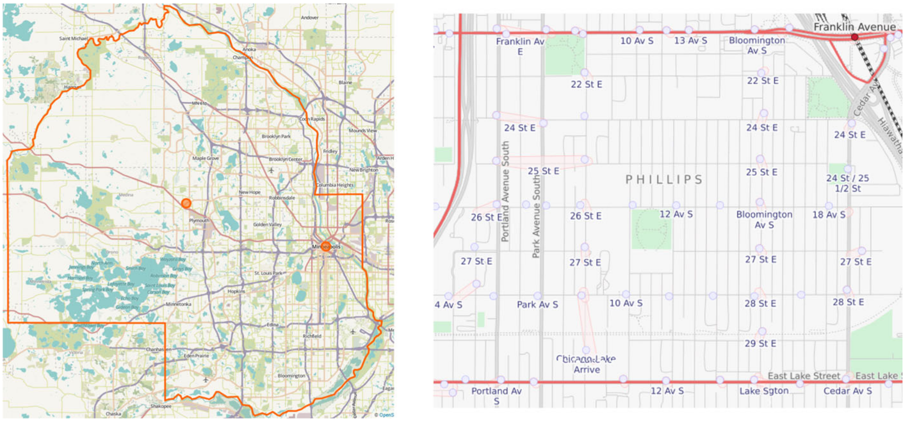
When the logarithmic Eq. (11) is used, the estimated regression equation is calibrated as in Table 2. It appears that in almost every test, the logarithmic Eq. (11) interprets better than the ratio Eq. (6).

4.2 Case of Hennepin County of Minnesota

We found that our regressed equation in Table 1 from even simulation fitted an actual situation well. The Minnesota Department of Transportation posted the following collector and local road VMT data publicly for the urban area within the Hennepin County that encompasses Minneapolis of the Twin Cities, MN as in Fig. 7a (Minnesota Department of Transportation 2015).

Table 2 Regression Equation of lnQ_L

Regression Equation	β	R^2	Error (%)	Sample Size
$3.64ln(Q_C) + 3.90ln\rho_M + 5.35ln\rho_C - 3.51ln\rho_L - 3.28$	(0, 1.4]	0.41	45.92 %	10
$0.43ln(Q_C) + 1.37ln\rho_M - 0.14ln\rho_C - 1.24ln\rho_L + 8.81$	(1.4, 2.0]	0.48	18.98 %	14
$-0.02ln(Q_C) + 0.19ln\rho_M - 0.54ln\rho_C - 0.60ln\rho_L + 7.37$	(2.0, ∞)	0.74	7.61 %	11



(a) (b)

Fig. 7 (**a**) Map of Hennepin County; (**b**) Example layout of road structure in Minneapolis. (*Source*: www.openstreetmap.org)

Figure 7b illustrates representative local road structure in the Minneapolis metropolitan area. Obviously, the local streets are on well connected grid networks. Our ratio-based regression equation in Table 1 with $\beta \in (1.4, 2.0]$ turns out to be a good fit as evidenced in Table 3. However, if we apply Eq. (6) to the raw data in Table 3, we are able to obtain a regression equation $\widehat{\frac{Q_L}{Q_C}} = 1.29\frac{\rho_M}{\rho_C} + 4.43\frac{\rho_M}{\rho_L} - 0.71$, with $R^2 = 0.86$, a much better fit. Its estimation errors are distinctly smaller than that from directly borrowing the equation in Table 1. Note that applying the regression equations across years to the Minneapolis network implies that the road densities of classifications and the land use do not change significantly and that we treat data from each year with an equal weight.

The state posted VMT data are often problematic because the formulas used for the calculation are often lack of justification. However, the Hennepin County data appears credible because extensive sampling was conducted to obtain the local road VMT estimates, although no error analysis of it is conducted. Table 3 shows that Equation (6) applies well in (at least some) fairly uniformly spaced grid networks.[1]

Similarly, if we apply Eq. (11) to the raw data in Table 4, we can obtain a logarithmic regression equation $ln\widehat{Q_L} = 16.041 - 0.174ln(Q_C) + 0.138ln\rho_M - 0.176ln\rho_C + 0.683ln\rho_L$, with $R^2 = 0.98$, a near perfect fit.

5 Discussion of Model Calibration

There are 'noises' that defy the ideal situation assumed for derivation of the results as in Eqs. (5), (7) and (19). Therefore, we propose Eqs. (6) and (11) to account for

[1]Caution that this assumes the Hennepin County data is accurate, an unverified assumption though. In this sense, the simulation results earlier appear more reliable.

Table 3 Urban Local Road VMT Estimation for Hennepin County, MN Using Density Ratios

Year	$\frac{\rho_M}{\rho_C}$	$\frac{\rho_M}{\rho_L}$	Q_L	Equation in Table 1		Re-calibrated Equation (6)	
				$\widehat{Q_L}$	Error(%)	$\widehat{Q_L}$	Error(%)
2007	1.08	0.16	3231129	3681670	13.94	3333216	3.16
2008	1.11	0.16	3366306	3536867	5.07	3240114	3.75
2009	1.13	0.16	3367607	3548667	5.38	3292573	2.23
2010	1.16	0.16	3382411	3706335	9.58	3498739	3.44
2011	1.23	0.16	3489908	3484007	0.17	3458759	0.89
2012	1.23	0.16	3505371	3419481	2.45	3414263	2.60
2013	1.23	0.17	3505886	3565450	1.70	3483399	0.64
2014	1.27	0.17	3505795	3527360	0.62	3574040	1.95
Average	–	–	–	–	4.86	–	2.33

those ‘noises’ through a calibration process. Those ‘noises’ mainly fall into several categories as described below.

- Uneven spatial distribution of road network for each functional class.
- Non-uniform directional distribution of trip destinations and non-uniform spacial distribution of trip origins in the local community.
- Through traffic traversing local or collector roads with neither ends being in the area. Or ‘local’ traffic with both ends in the local community.
- Poor or uneven connectivity of local and collector roads.

Given all these ‘noises’, however, we believe the following fact holds: each traveler maintains a statistically stable actual VMT on local roads relative to collector road VMT. Our confidence in the utility of our proposed models also rests on the

Table 4 Urban Local Road VMT Estimation for Hennepin County, MN Using Logarithmic Terms

Year	$ln(Q_C)$	$ln\rho_M$	$ln\rho_C$	$ln\rho_L$	Q_L	Equation (11)	
						$\widehat{Q_L}$	Error(%)
2007	14.69	0.35	0.27	2.19	3231129	3217653	0.42
2008	14.63	0.41	0.30	2.23	3366306	3334910	0.93
2009	14.62	0.42	0.30	2.23	3367607	3355714	0.35
2010	14.66	0.43	0.28	2.23	3382411	3353082	0.87
2011	14.59	0.43	0.23	2.24	3489908	3443125	1.34
2012	14.57	0.43	0.23	2.25	3505371	3476540	0.82
2013	14.57	0.43	0.22	2.26	3505886	3495724	0.29
2014	14.58	0.47	0.23	2.25	3505795	3497266	0.24
Average	–	–	–	–	–	–	0.66

fact that the travel patterns do not have noticeable change as long as the land use and the demographic structure do not dramatically change for a metropolitan area. In other words, as long as residential, work, shopping and other activity locations and road spacing do not change distinctly, our models appear to have little need to be re-calibrated. Periodic calibration of the regression formula, such as once in a few years, would allow to reflect the land use and demographic changes. Another source of errors, through traffic on city roads account for less than 0.2 % of the total VMT in light of Levinson and Zhu (2012), which appears ignorable in general.

Important is how to collect data to calibrate Eq. (6) and (11). Our goal is to statistically estimate the local road VMT by reflecting local road travel characteristics: proximity of trip origins to collector roads and trip purposes (work, school, shopping), which entails an itinerary survey and statistical analysis. An itinerary survey records all the origins and destinations and routes of survey participants during a particular period of time, including both work days and weekends.

Itinerary survey is technically feasible today. An application may be developed and be installed in smart phones. Upon participants' agreement, itinerary data is periodically uploaded to a server for analysis. For each trip, the local, collector and minor arterial road VMTs are recorded. Such an itinerary survey would entail a tremendous amount of financial resources and labor, which is beyond the scope of this research. Nevertheless, a practical procedure would be necessary as follows.

- Step 0: Initialization. Categorize an area of interest into neighborhoods. Neighborhoods have different β values and each neighborhood will be used as a data point.
- Step 1: Conduct an itinerary survey according to participants' residence, age, sex, profession, and etc. This sample shall be representative of the demographic population, residential distribution in neighborhoods of different β value. Note that each participant may have trips of several different purposes such as work, shopping and social activities with their according origin-destinations.
- Step 2: Tabulate the VMT on roads of different classes and neighborhoods of different β indice in which the trips are originated.
- Step 3: Conduct parameter calibration for Eq. (6) and (11) using neighborhoods of different β values respectively. Regression equations are resulted from this step.

The resulting regression equations will be applied to according neighborhoods for prediction of local road VMT. Between Eqs. (6) and (11), we would suggest using (11) based on our numerical tests. Our current results appear to apply well to urban neighborhoods with grid networks of streets. Additional work is needed for rural neighborhoods, which is a limitation of our results here.

6 Conclusion

In this paper, we propose new models to estimate local road vehicle miles traveled (VMT). VMT estimation in general has strong policy implications in the U.S. because the estimates are directly used in the formulas for allocation of highway apportionment fund to states. The VMT numbers are often the basis for analyzing gas consumption and environmental pollution as well. However, traditionally, there has not been a consistent method for the local road VMT estimation. The rationale in our paper is that collector road VMT estimates are more reliable and easier to manage than its local road counterpart. Therefore, instead of directly calculating local road VMT through costly local road traffic count, this paper explores how local VMT compares with collector road VMT, and unveils a strong relationship between local and collector road VMTs so that collector road VMT may be used for estimating its local road counterpart. In a similar fashion, one may estimate collector road VMT by using minor arterial road VMT because generally the higher functional classification VMTs are more accurate.

This paper resides on a premise that VMT ratio between local and collector roads is primarily determined by the roadway network structure instead of by household demographic characteristics. The research starts with idealistic situations in which demand and roadway spacing are uniformly distributed, which allows development of analytical formulas and also enables to find interpretive factors of the VMT ratio. A major finding, the idealistic derivation reveals density ratios as key terms such as $\frac{\rho_M}{\rho_L}$ and $\frac{\rho_M}{\rho_C}$, etc. More specifically, we have identified $\frac{\rho_M}{\rho_L}$ and $\frac{\rho_M}{\rho_C}$ as effective factors interpreting $\frac{Q_L}{Q_C}$, and $ln\rho_M$, $ln\rho_C$ and $ln\rho_L$ as effective factors interpreting $ln(Q_L)$-$ln(Q_C)$. In the former case, we further examine circular shaped communities to have confirmed the robustness of the key interpreting term $\frac{\rho_M}{\rho_C}$ to road network shapes. These key terms allow establishing regression equations that may be calibrated with field data for easy practical use. We expect field data calibration to account for actual road spacing, which defies the idealistic situation assumed. Similarly, by reducing the road classifications by one level, prediction of collector road VMT using minor arterial road VMT becomes prediction of local road VMT in this paper. Therefore, one may propose similar equations for prediction of collector road VMT as discussed in details in Cao (2015).

We have further conducted computer simulations to confirm the interpretive power of those identified explanatory variables. 35 communities, each with a different local road pattern, are generated by following established literature. Trips are assumed to first go by local roads onto collector roads before sequentially getting onto minor and principal arterial roads. The VMT data from simulation for the classes of roadways are used to assess fitness of the proposed regression equations. Equally impressively, the regressed equations from simulation are found to fit in the Hennepin County urban area VMT data well.

We have also proposed a procedure to apply and calibrate the regression equations. Our suggestion is that individual surveys about daily trips regarding local and collector road mileages, provided that adequate mix of participants with representative socioeconomic characteristics such as occupation, age, ethnicity, gender, and household size are ensured, shall be conducted whenever there is a significant change to the land use in an urban area. If there is no significant change in land use or demographic characteristics such as population and its composition, there does not appear to be a compelling reason to re-calibrate, which saves on costly annual surveys. Note that our models so far only appear to apply well to urban communities with grid roadway network and do not apply well to rural areas with sparse roads and poor road connectivity.

Acknowledgments Jiayu Qian in his MS thesis laid much ground work for development of this paper. His hard and careful efforts are gratefully acknowledged. A reviewer helped improve the presentation significantly through many comments, one of which led to the addition of Section 3.1.1. The paper also benefited from Drs. Mark Burris and Bill Eisele's inputs through the process of the second author's thesis.

References

Cao X (2015) Estimating vehicle miles of travel on low functional classes of roadways, Texas A&M University. Master's thesis

Christofides N, Eilon S, Watson-Gandy C (1971) Distribution management: mathematical modeling and practical analysis. Griffin, London

Daganzo CF (1984) The length of tours in zones of different shapes. Transp Res B Methodol 18(2):135–145

Dill J (2004) Measuring network connectivity for bicycling and walking. In: 83rd Annual Meeting of the Transportation Research Board, Washington, DC, pp 11–15

Federal Highway Administration (FHWA) (2013) Highway functional classification concepts, criteria and procedures, FHWA, U.S. Department of Transportation. Available at http://www.fhwa.dot.gov/planning/processes/statewide/related/highway_functional_classifications

FHWA (1992) Safety effectiveness of highway design features. Volume I, Access Control

Frawley WE (2002) Local street vehicle miles traveled (vmt) random count site selection for counties that have air quality conformity issues, Texas A&M Transportatoin Institute. Work Report

Fricker J, Kumapley R (2002) Publication FHWA/IN/JTRP-2002/10, Joint Transportation Research Program Updating procedures to estimate and forecast vehicle-miles traveled. Indiana Department of Transportation and Purdue University, West Lafayette, Indiana

Hausman J (2011) Office of Highway Policy Information US Functional classification guidance update. Federal Highway Administration, Washington, D.C

Holroyd E (1966) Theoretical average journey lengths in circular towns with various routeing systems, report 43. Transport and Road Research Laboratory, Crowthorne, Berks

Kumapley R, Fricker J (1996) Review Of methods for estimating vehicle miles traveled

Levinson D, Zhu S (2012) The hierarchy of roads, the locality of traffic, and governance. Transp Policy 19:147–154

Miller AJ (1967) On spiral road networks. Transp Sci 1(2):109–125

Minnesota Department of Transportation (2015) Minnesota Department of Transportation: roadway data – Vehicle Miles Traveled (VMT). Available at www.dot.state.mn.us/roadway/data/data-products.html#VMT

Newell GF (1980). Traffic flow on transportation networks. MIT Press

Oakridge National Laboratory (2011) Developing a best estimate of annual vehicle mileage for 2009 Nhts vehicles. FHWA National Household Travel Survey, Work Report

Parthasarathi P, Hochmair H, Levinson D (2012) Network structure and spatial separation. Environment and Planning B: Planning and Design 39(1):137–154

Parthasarathi P, Hochmair HH, Levinson DM (2015) Street network structure and activity spaces. Urban Stud 52(6):1090–1112

Pearce C (1974) Locating concentric ring roads in a city. Transp Sci 8(2):142–168

Qian J (2013) Estimating vehicle miles traveled on local roads, Texas A&M University. Master's thesis

Rentziou A, Gkritza K, Souleyrette RR (2012) Vmt, energy consumption, and ghg emissions forecasting for passenger transportation. Transp Res A Policy Pract 46(3):487–500

Rodrigue J-P, Comtois C, Slack B (2013) The geography of transport systems, Routledge

Saidi S, Wirasinghe S, Kattan L (2016) Long-term planning for ring-radial urban rail transit networks. Transp Res B Methodol 86:128–146

Seaver W, Chatterjee A, Seaver M (2000) Estimation Of traffic volume on rural local roads

Smeed RJ (1970) The effect of the design of road network on the intensity of traffic movement in different parts of a town with special reference to the effects of ring roads. In: Tewksbury Symposium. University of Melbourne

Southworth M, Ben-Joseph E (2013) Streets and the shaping of towns and cities, Island Press

Stone B, Obermann W, Snyder S (2005) A new method for estimating and projecting vehicle miles of travel: linkages to landscape change and ozone impacts to northern forests, US Department of Transportation. General Technical Report NC-253

Xie F, Levinson D (2007) Measuring the structure of road networks. Geographical analysis 39(3):336–356

Zhong M, Hanson BL (2009) Gis-based travel demand modeling for estimating traffic on low-class roads. Transp Plan Technol 32(5):423–439