Individual speed variance in traffic flow: analysis of Bay Area radar measurements

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Abstract

The recent increase of mobile devices able to measure individual vehicles speed and position with improved accuracy brings new opportunities to traffic engineers. The large amount of individual probe measurements allows the study of phenomena previously unobservable with conventional sensing technologies, and the design of novel traffic monitoring and control strategies. However, challenges inherent to the use of speed and location data arise. One of the main challenges of measurements collected from individual vehicles lies in their ability to provide relevant information on the macroscopic properties of traffic flow. According to the classical triangular fundamental diagram, the relation between speed and flow can be inversed in the congestion phase but not in the uncongested phase. In the latter, the flow of vehicles cannot be retrieved from the speed of vehicles, assumed to be constant. This article proposes to investigate the nature of the relationship between flow and speed from joint measurements from radar data. Two different regression methods are proposed in this article to estimate traffic flow based on individual speed measurements: regression of flow on speed and regression of flow on speed variance. The respective performance of these two methods during specific traffic periods is assessed, and recommendations on their relative strengths are provided. This empirical study is conducted using 112 NAVTEQ radars [1] measuring speed and flow on highways in the San Francisco Bay area, California.

I. Introduction

The recent years have witnessed an unprecedented growth in the number of traffic data sources from connected mobile devices such as cell phones or cellular devices and embedded GPS. In contrast to conventional loop detectors which output counts of vehicles and occupancies (i.e. flows) that in turn can be used to estimate velocities, these new widely spread sources only provide velocity and location information. The understanding of the type of phenomena measurable by individual vehicles and their relation with classical sensors is critical to the development of novel fusion schemes and advanced control algorithms.

Classical macroscopic traffic flow theory has been historically articulated around flow and occupancy, which are the two quantities measured by loop detectors. Modeling research driven by this type of available measurements has proposed to model traffic flow as a compressible flow. Hydrodynamics models have been shown to perform well for simulation, estimation, and control applications. Some of the major difficulties regarding traffic data processing have been related to the necessary use of a so-called g-factor behaving as a proxy for vehicle lengths [2], and to the requirement for constant conversion between measured time-mean quantities and modeled space-mean quantities, involving the computation of variances [3].

The explosion of the amount of point speed measurements poses new challenges to traffic engineers. In particular, the great potential for combination or 'fusion' of loop and probe data requires improved understanding of the relation between point speed and point flow, and the design of novel tools for converting one type of quantity to the other.

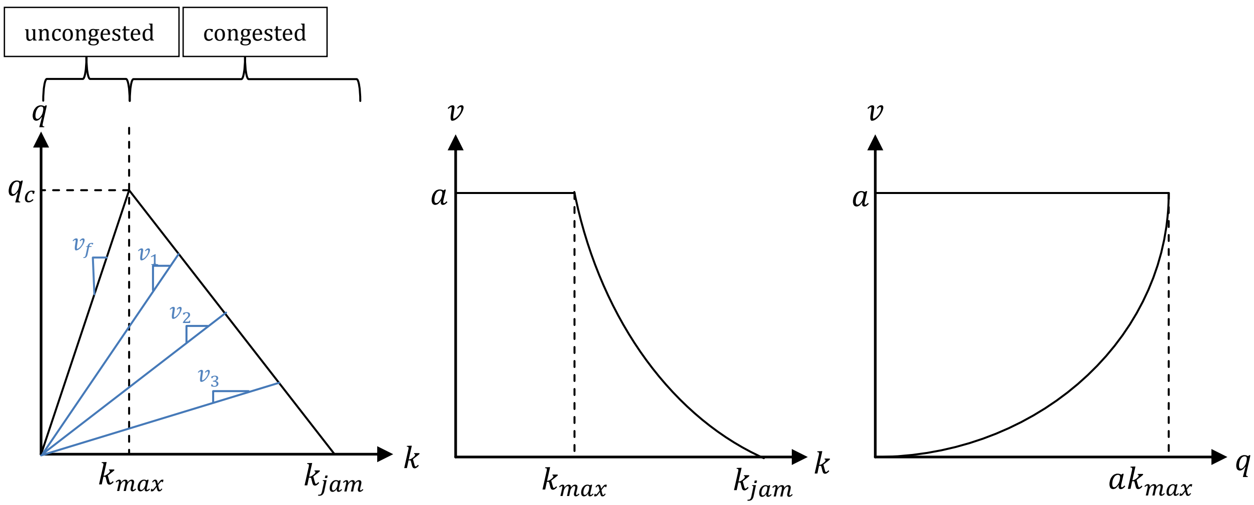
In this article, the empirical relation between point speed and point flow for 112 NAVTEQ radars [1] in the San Francisco Bay Area, California, is studied, with the goal of assessing the feasibility of inferring traffic flow from probe speed. A proposed relation between speed variance and flow is also investigated and the two methods, regression of flow over speed and regression of flow over speed variance, are compared on the real dataset.

The rest of the article is organized as follows. Section II presents fundamental concepts of traffic flow theory and the inherent difficulties associated with the conversion from speed to flow, a classical conversion method using regression of flow on speed, and a novel conversion method investigated in this article based on regression of flow on speed variance. Section III describes the dataset used and the methodology followed before proceeding onto discussing the obtained results in Section IV. Lastly, perspectives on the proposed conversion method based on the findings are given in Section V and concluding remarks are provided in Section VI.

II. General overview

A. Background and problem definition

The classical theory of traffic flow describes two traffic phases: the uncongested phase or free flow phase, and the congested phase. This approach has traditionally been captured with a so-called fundamental diagram. In particular, the *triangular fundamental diagram* [4] models the relation between traffic flow and density by a triangular relation (shown in the left subfigure of Figure 1). The speed-density and speed-flow diagrams are deduced using the fundamental traffic formula stating that for stationary conditions, flow is equal to speed times density i.e. $q = v(k).k$.



$$q = ak, \quad 0 \leq k \leq k_{max}$$
$$q = ck + d, \quad k_{max} \leq k \leq k_{jam}$$

$$v = a, \quad 0 \leq k \leq k_{max}$$
$$v = c + \frac{d}{k}, \quad k_{max} \leq k \leq k_{jam}$$

$$v = a, \quad uncongested$$
$$v = \frac{cq}{q - d}, \quad congested$$

Figure 1: Flow-density, speed-density, and speed-flow relationships (assuming triangular fundamental diagram).

As seen in the left subfigure of Figure 1, for a triangular fundamental diagram, the uncongested phase is characterized by a positive linear relation between flow and density i.e. $q = ak$ where a is a positive number. The associated velocity, noted v_f and equal to the slope of the line connecting the origin and the point of interest on the fundamental diagram, is the free flow velocity and is the highest theoretical velocity at which vehicles may travel on the corresponding roadway segment; it is constant in the uncongested phase and is equal to a in this case. The congested phase is characterized by a negative linear relationship between flow and density i.e. $q = ck + d$ where c is a negative number. As the associated speed is equal to the slope of the line connecting the origin with the point of interest on the fundamental diagram, speed decreases with density in this phase; this is illustrated in the middle subfigure of Figure 1.

In the uncongested phase, velocity remains constant at the free-flow speed. This models the fact that up to a certain threshold density, the spacing between vehicles travelling on a roadway segment is sufficiently large for commuters not to be affected or constrained by surrounding vehicles, and as such they travel at the free-flow speed.

As seen in the fundamental and speed-flow diagrams in Figure 1, the speed-to-flow conversion is straightforward in the congested phase as speed monotonically decreases with density in said state. In the uncongested phase, however, the conversion is theoretically impossible as speed is theoretically constant at the free-flow speed. The reader is referred to [5] and [6] for related research on the topic.

B. Learning improved speed/flow relation

A natural method of conversion consists in using a classical regression in speed-flow coordinates. Joint measurements of speed and flow are gathered in a learning phase, and a linear regression is run on the data corresponding to the uncongested state. As is empirically shown in a subsequent section of this report, this method yields results that are not always accurate and provides only a “blurred” picture of ground truth flow. A competing technique is thus desirable.

This article proposes and investigates the performance of an alternative conversion technique based on individual speed variances. The intuition behind it is the following: **in the uncongested phase, at low flows, commuters are able to drive at the speed they feel comfortable with; hence individual speed variance is expected to be relatively large. At higher flows, however, in the uncongested phase, the individual speed variance is expected to be relatively small because commuters are constrained by other surrounding vehicles and hence cannot freely choose their traveling speeds**. This hypothesis therefore postulates a decreasing relationship between individual speed variance and flow in the uncongested phase.

III. Data and methodology

A. Data source and format

The dataset used in this analysis consists of speeds and flows of vehicles travelling on highway and freeway segments, as recorded by 112 radars in the Bay Area, California, during the month of September 2010. The radars output speed (miles per hour) and flow (vehicles per minute) measurements per lane of roadway for every minute of every hour of every day. The raw data was derived from NAVTEQ Traffic Patterns™ and made available to the California Center for Innovative Transportation courtesy of the NAVTEQ University Program (http://www.NN4D.com/university). Traffic Patterns data © 2011 NAVTEQ.

B. Methodology

The validity of the proposed speed-to-flow conversion method is assessed by computation of different statistics for each of the 112 available radars. The following sections discuss the experimental procedures considered.

1. Aggregate speed/flow diagrams

The aggregate speed/flow diagrams are relations between speed and flow at the radar location. Total flow in every minute is simply the sum of the flows on each lane during that minute. In other words, total flow is the number of cars traveling on the highway facility that pass the radar location every minute. Speed is the flow-weighted speed i.e. the average speed over all lanes weighted by the flow prevailing on each of these lanes. It reads:

$$\boxed{\bar{v} = \frac{\sum_{i=1}^{l} v_i q_i}{\sum_{i=1}^{l} q_i}}$$

where: $\bar{v}$ is the flow-weighted speed in the minute of interest
l is the number of lanes
v_i is the average speed of vehicles on lane *i* in the minute of interest
q_i is the flow on lane *i* in the minute of interest

The interested reader is referred to [7] for more information concerning flow-weighted speed quantities. If all flows are equal to zero, the flow-weighted speed is not defined as there is no car passing by and hence there is no speed for which we can compute an 'average'. Note however that this is a very rare case.

2. Variance computation

In the process of evaluating the relationship postulated to exist between speed variance and flow, four different speed variances are computed. These are defined below and described in greater detail in the subsequent sections:

- Variance over time of Flow-Weighted Speeds: This variance is noted as $\boldsymbol{Var_t^{as}}(\boldsymbol{v})$ where the subscript 't' stands for time and the superscript 'as' stands for *aggregated speeds*.
- Variance over time of Individual-Lane Speeds: This variance is noted as $\boldsymbol{Var_t^{is}}(\boldsymbol{v})$ where the subscript 't' stands for time as before and the superscript 'is' stands for *individual speeds*.

- Variance over flow of Flow-Weighted Speeds (speeds higher than critical speed): This variance is noted as $\boldsymbol{Var_f^{as}(v)}$ where the subscript 'f' stands for flow and the superscript 'as' stands for aggregated speed.
- Variance over flow of Individual-Lane Speeds (speeds higher than critical speed): This variance is noted as $\boldsymbol{Var_f^{is}(v)}$.

The computation of the variance over flow is required for evaluating the relationship between speed variance and flow and assessing the existence of a decreasing relation between the two quantities.

The variance over time is computed for estimating the flow from the speed variance under the assumption of local traffic stationarity. Indeed, in a practical setting where no loop detector is available, the speed variance for a given flow cannot be computed since no flow measurement is available. Hence the speed variance over time, which is the only quantity which can be computed from streaming point speed, is used equivalently under the assumption of local stationarity.

a) Variance over time

(1) Aggregate speeds

The variance over time of the aggregate speeds is the variance of the flow-weighted speeds (computed earlier) in every time interval of t minutes. In this work the size t of the time intervals is taken to be 10 minutes in order to have sufficient values for computing the variance without having to discard the assumption of stationary traffic state over the time interval. As radars report data every minute, a size t of 10 minutes means 10 values of flow-weighted speeds are used for every variance calculation. Mathematically, this variance is computed according to the following equation:

$$\boxed{Var_t^{as}(v) = \frac{1}{t-1}\sum_{i=1}^{t}\left(\overline{v_{ij}} - \overline{\overline{v}}_j\right)^2}$$

where: t is the number of values in time interval j

$\overline{v_{ij}}$ is flow-weighted speed i in time interval j

$\overline{\overline{v}}_j$ is the average flow-weighted speed in time interval j : $\frac{1}{t}\sum_{i=1}^{t}\overline{v_{ij}}$

(2) Individual speeds

The variance over time of the individual speeds is the variance of the individual-lane speeds on all lanes in every time interval of t minutes. It is computed from k values of individual speeds where k is equal to t times the number of lanes on the highway/freeway facility. Mathematically, it is calculated according to the following equation:

$$\boxed{Var_t^{is}(v) = \frac{1}{lt-1}\sum_{i=1}^{lt}\left(v_{ij} - \overline{v_j}\right)^2}$$

where: l is the number of lanes of the roadway segment at the radar location of interest

t is the time interval size in minutes

v_{ij} is the average vehicle individual-lane speed in the minute of interest in time interval j

$\overline{v_j}$ is the average vehicle individual-lane speed over time interval j: $\frac{1}{lt}\sum_{i=1}^{lt} v_{ij}$

b) Variance over flow

(1) Aggregate speeds

The variance over flow of the aggregate speeds is the variance of the flow-weighted speeds corresponding to every value of flow. Since we are interested in the relation between speed variance and flow of vehicles in the uncongested state, speed values corresponding to the congested state should not enter the variance calculation. As such, a threshold or critical speed, noted as v_c and defined as the speed at which the congested and uncongested branches of the speed/flow diagram intersect, is identified for each radar.

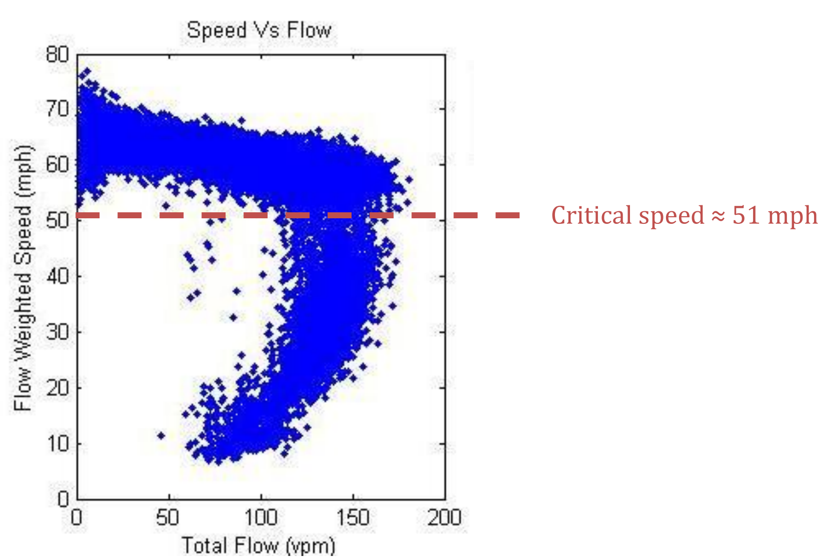


Figure 2: Illustration of critical speed using speed/flow diagram for radar 165421.

As seen in Figure 2, the critical speed is the speed corresponding to the intersection of the two clouds of points representing the uncongested and congested states respectively. After identifying the critical speed, the variance over flow of the aggregate speeds is computed for each value of flow taking only speed values that are larger or equal to the critical speed (the congested branch is only described and its speed values do not enter any calculations).

Mathematically, this variance is computed according to the following equation:

$$\boxed{Var_f^{as}(v) = \frac{1}{n-1}\sum_{i=1}^{n}\left(\overline{v_{iq_j}} - \overline{\overline{v_{q_j}}}\right)^2 \; with \; \overline{v_{iq_j}} \geq v_c \forall\, i}$$

where: n is the number of flow-weighted speed values that correspond to a flow of q_j and a speed greater or equal to v_c

$\overline{v_{iq_j}}$ is the flow-weighted speed i having a flow of q_j

$\overline{\overline{v_{q_j}}}$ is the average flow-weighted speed having a flow of q_j = $\frac{1}{n}\sum_{i=1}^{n}\overline{v_{iq_j}}$

(2) Individual Speeds

The variance over flow of the individual speeds is the variance of all individual-lane speeds whose corresponding flows sum up to a certain value of total flow. For every value of total flow, all speeds whose flows sum to that total flow are identified and their variance computed. Mathematically, it reads as follows:

$$\boxed{Var_f^{is}(v) = \frac{1}{m-1}\sum_{i=1}^{m}\left(v_{iq_j} - \overline{v_{q_j}}\right)^2 \; with \; v_{iq_j} \geq v_c \forall\, i}$$

where: m is the number of flow-weighted speed values whose corresponding flows sum to q_j in any minute

v_{iq_j} is the individual-lane speed i whose value is greater or equal to v_c and whose flow, when summed with the other individual- lane flows of the given minute, adds to q_j

$\overline{v_{q_j}}$ is the average individual-lane speed = $\frac{1}{m}\sum_{i=1}^{m} v_{iq_j}$

Table 1: Summary of the different computed variances.

Variance	Notation	Equation
Variance over time of flow-weighted speeds	$Var_t^{as}(v)$	$\frac{1}{t-1}\sum_{i=1}^{t}\left(\overline{v_{ij}} - \overline{\overline{v_j}}\right)^2$
Variance over time of individual-lane speeds	$Var_t^{is}(v)$	$\frac{1}{lt-1}\sum_{i=1}^{lt}\left(v_{ij} - \overline{v_j}\right)^2$
Variance over flow of flow-weighted speeds higher than critical speed	$Var_f^{as}(v)$	$\frac{1}{n-1}\sum_{i=1}^{n}\left(\overline{v_{iq_j}} - \overline{\overline{v_{q_j}}}\right)^2, \overline{v_{iq_j}} \geq v_c \;\forall\, i$
Variance over flow of individual-lane speeds higher than critical speed	$Var_f^{is}(v)$	$\frac{1}{m-1}\sum_{i=1}^{m}\left(v_{iq_j} - \overline{v_{q_j}}\right)^2, v_{iq_j} \geq v_c \;\forall\, i$

3. Regression models

a) Speed/flow regression

The conventional method of conversion is based on a linear regression. Data is gathered about speed and flow, and speeds in the uncongested state are then linearly regressed on flow. The regression allows the estimation of the coefficients of the following model:

$$\boxed{v(q) = \beta_0 + \beta_1 q}$$

where v is velocity
q is flow
β_0 is the intercept which is the speed at 'zero' flow and density
β_1 is the regression line slope which can be thought of as the spacing in free flow

In this study, the regression is done using a subset consisting of data for one week only; all speeds that are greater or equal to the critical speed (pre-determined using the data for the whole month) for the radar of interest are regressed onto their respective flows.

After calibrating the model by determining the 'beta' coefficients using ordinary least-squares regression [8], the performance of the model is assessed by comparing the estimated flow from speed data with the observed data, for the week following the week of the data used for calibration. The flow estimate is determined by inverting the calibrated model so as to have flow as a function of speed:

$$\boxed{q(v) = \frac{1}{\beta_1} v - \frac{\beta_0}{\beta_1}}$$

$q(v)$ and v belong to the uncongested phase

b) Speed variance/flow regression

The speed variance/flow regression is defined as:

$$\boxed{Var(v) = \alpha_0 + \alpha_1 q}$$

where $Var(v)$ is the speed variance
q is the flow

The speed variance here is the variance over flow of the individual speeds described in the previous section and noted $Var_f^{is}(v)$. As with the speed/flow regression method, this method is calibrated using flow data and associated speed variances for one week in September. If the speed variance/flow relationship exhibits two or more domains with significantly different slopes, a separate regression is done on each domain separately, in order to have a piecewise linear relationship such as the one shown in Figure 3.

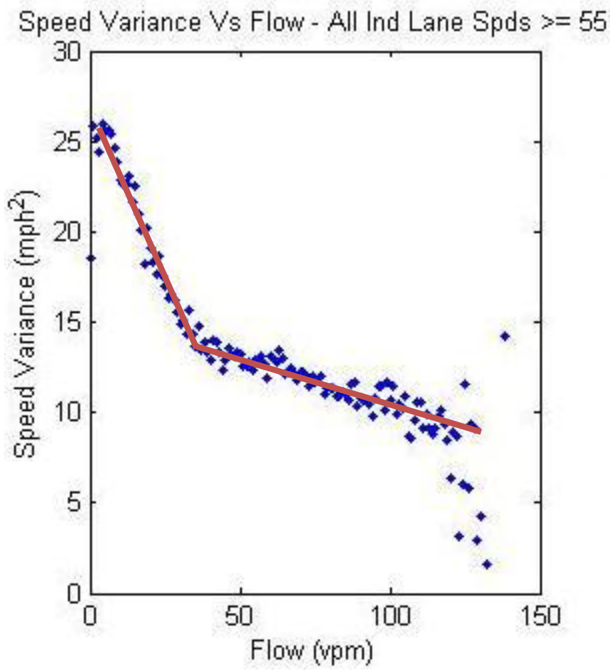


Figure 3: Example of piecewise linear regression of speed variance over flow.

Similarly, the model performance is assessed by inverting the previous equation and comparing the flow estimate with the observed flow using data corresponding to the week that follows the week used for calibration. The inverted equation is:

$$\boxed{q(Var(v)) = \frac{1}{\alpha_1} Var(v) - \frac{\alpha_0}{\alpha_1}}$$

It is to be reminded that the speed variance in the model is $Var_f^{is}(v)$ as described earlier. A priori knowledge of flow is not known however and therefore it is not possible to identify all individual speed values that have flows that sum up to a certain total flow value in order to compute their variance. Hence, an assumption of locally stationary traffic is required. Total flow is consequently assumed to be constant over each time interval and speed variance is computed by computing the variance of all individual-lane speeds in each time interval, excluding those speeds under the predetermined critical speed for the radar of interest. The flow is then determined from the calibrated model and is compared with the observed flow prevailing in the corresponding time interval.

IV. Results

A. Aggregate speed/flow diagrams

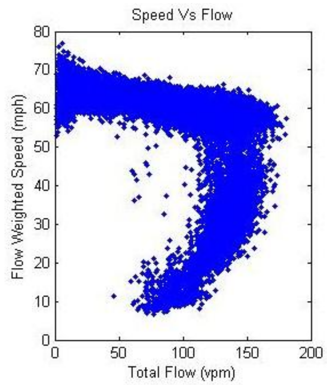
The main characteristics of the speed-flow diagrams and their frequency of appearance for 109 radars are outlined in Table 2.

Table 2: **Speed/flow diagrams characteristics and frequency of appearance.**

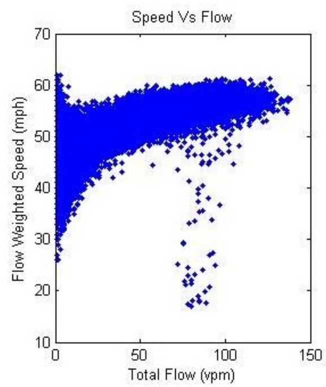
Unconongested Branch in *(q,v)* coordinates (UC)	
Decreasing Linearly (1)	36
Increasing Linearly (2)	26
Flat (3)	27
Increasing Non-Linearly (4)	11
Non-Linear (5)	9
Total	**109**
Congested Branch in *(q,v)* coordinates (C)	
Linear Vertical (6)	13
Linear Inclined (7)	27
Curved (8)	40
Not Appearing (9)	29
Total	**109**
Other in *(q,v)* coordinates	
Congested branch is spread out across a large range of flow (10)	22
Large variance of speeds at small flows (11)	30
Existence of C-like branch at small flows (12)	4

The characteristics of the 'Uncongested Branch' and 'Congested Branch' sections in the table partition the radars sample i.e. each plot exhibits one and only one of the indicated characteristics. That is not the case for the 'Other' section where a given plot may exhibit any combination of the three properties. 3 radars out of 112 provide highly irregular data and are discarded from the analysis.

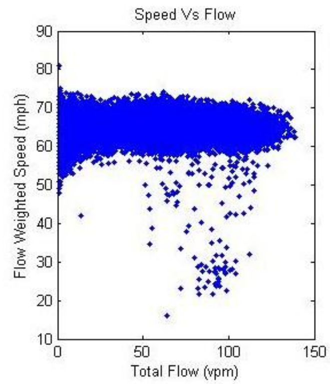
Examples of each of the properties indicated in Table 2 are presented in Figure 4.



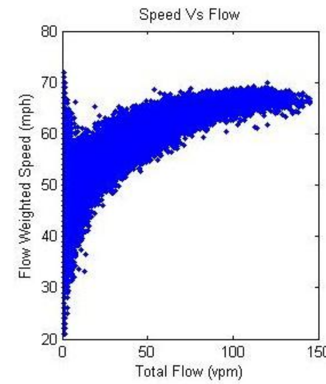
Radar 165421 – Example of 1 and 8 (refer to table 2)



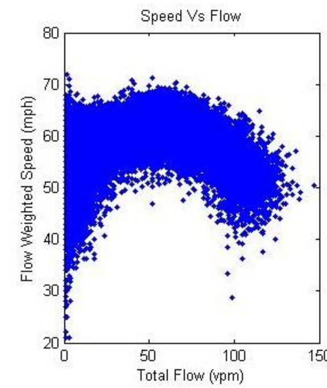
Radar 152153 – Example of 2 and 9



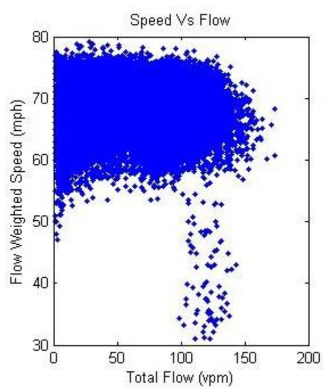
Radar 152103 – Example of 3 and 10



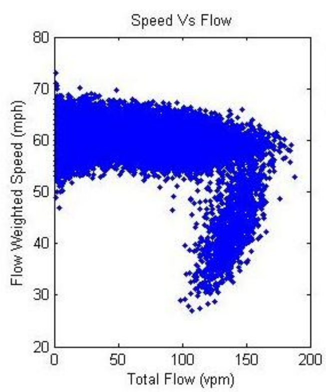
Radar 151595 – Example of 5, 9, and 11



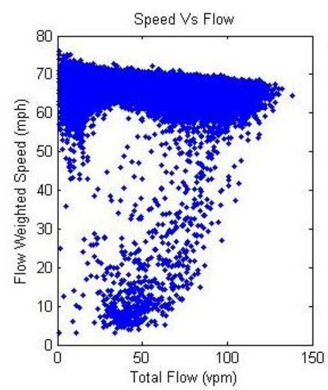
Radar 165475 – Example of 6, 9, and 11



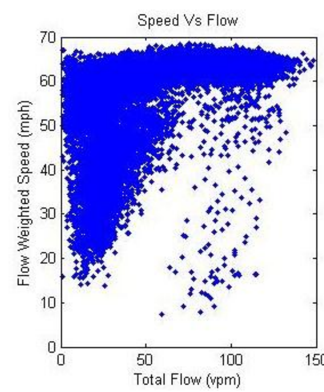
Radar 152081 – Example of 3 and 7



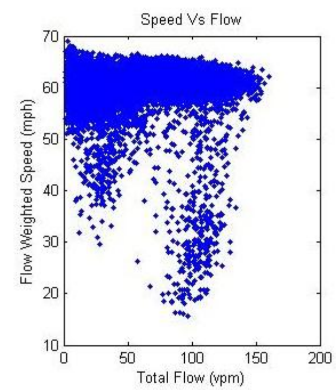
Radar 152061 – Example of 1 and 8



Radar 152203 – Example of 1, 9, and 10



Radar 152227 – Example of 6, 9, 11, 12



Radar 152177 – Example of 1, 9, 10, and 12

Figure 4: **Examples of the different characteristics of the observed speed/flow diagrams.**

B. Speed variance/flow relationship

Different types of relationships are observed between speed variances and flow. In particular, 39 of the 112 radars exhibit a decreasing speed variance with flow. Examples of these are presented in Figure 5.

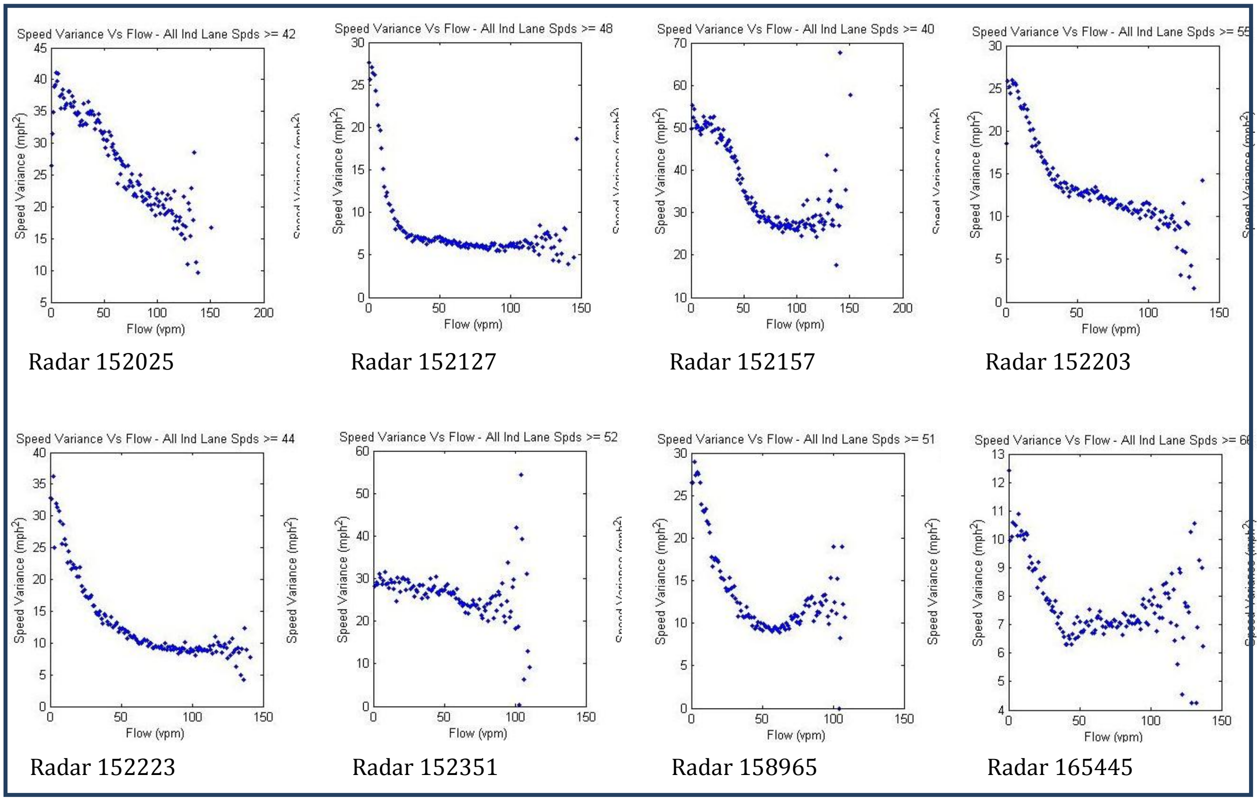


Figure 5: Examples of Variance Plots with Speed Variance Decreasing with Flow

C. Calibration and performance

As indicated in the previous section, the models are calibrated using data from one week in September (Monday 13th to Sunday 19th) and validated using data from the following week of September (Monday 20th to Sunday 26th). The performance of the two regression models are illustrated for radars 152157 and 165493 in Figure 6 and 7 respectively, with the following legend:

◆ Observed flow from radar

◆ Estimated flow from calibrated regression model

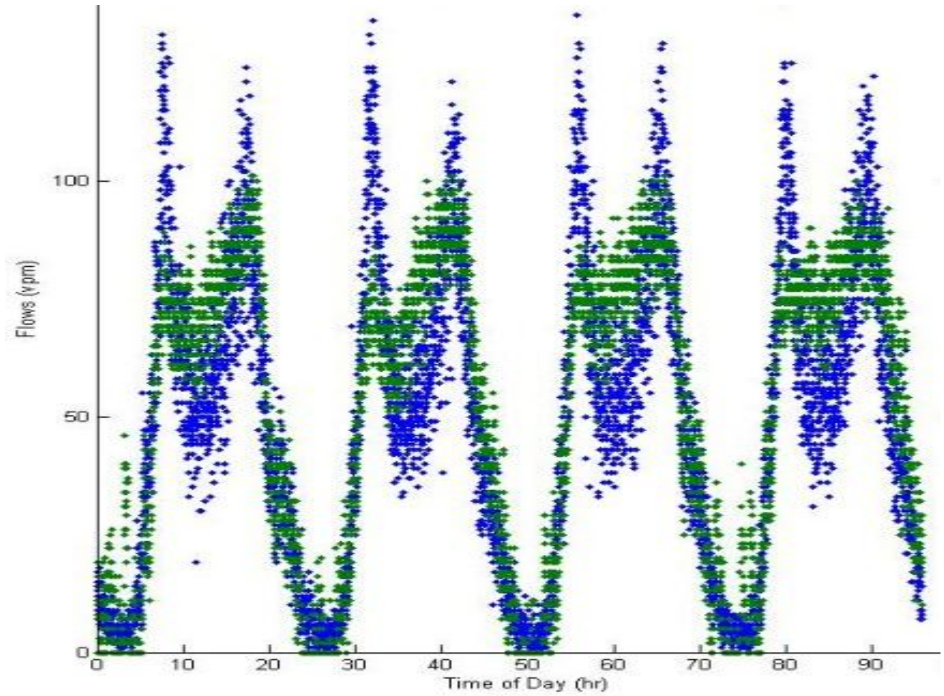


Figure 6: **Observed and estimated flow for radar 152157, speed to flow regression.**

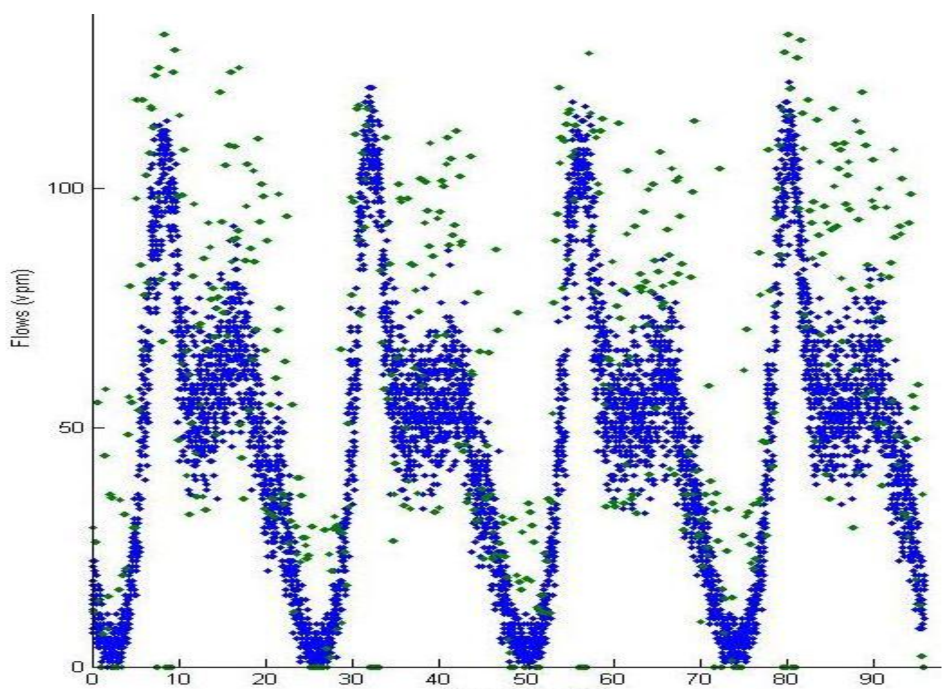


Figure 7: **Observed and estimated flow for radar 165493, speed variance to flow regression.**

V. Discussion and analysis

A. Speed variance/flow taxonomy

Distinctive properties of the relationship between speed variance and flow can be noted to impact the accuracy of the speed variance method.

- Radars and time periods for which an increasing relation exists between speed variance and flow exhibit higher correlation between the estimated flow and the observed flow.
- Radars and time periods for which a decreasing relation exists between speed variance and flow tend to exhibit speed/flow diagrams with an uncongested branch that is increasing in flow/speed coordinate, a large variance of speeds at low flows, and a congested branch that is very light (see Figure 8).

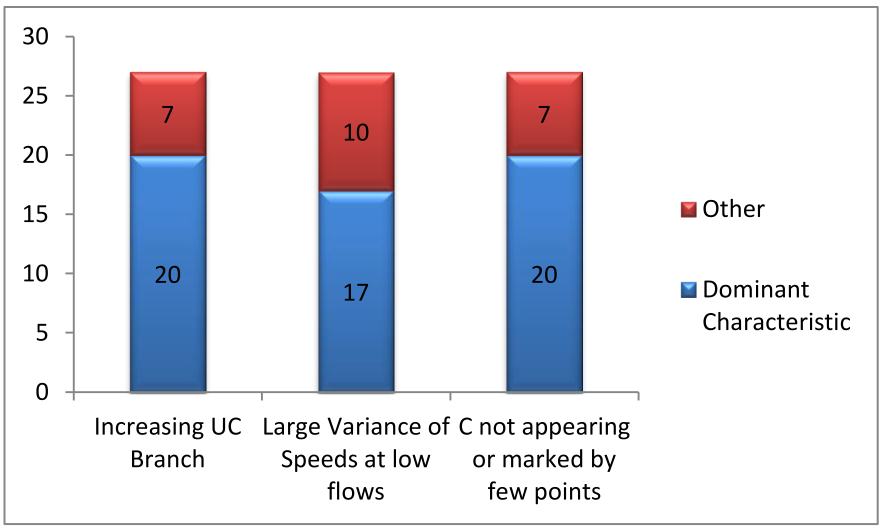


Figure 8: Frequency of appearance of major characteristics of speed/flow diagrams associated with time plots exhibiting a decreasing relation between speed variance and flow.

On the other hand, as illustrated in Figure 9, the distribution of profiles of speed/flow diagrams is fairly uniform for the case of linear relation between speed variance and flow.

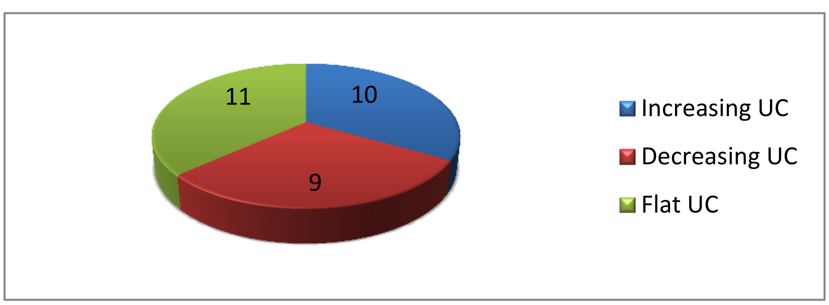


Figure 9: Distribution of the three types of uncongested branches across the speed/flow diagrams associated with the 30 radars exhibiting a linear relation between speed variance and flow.

B. Performance of speed / flow method

This model is able to predict flows with more accuracy both in terms of magnitude and trend. It can be noted that an increasing uncongested branch in *(q,v)* coordinates tends to improve the accuracy of the results.

The accuracy of the results tends to deteriorate quickly (both in terms of magnitude and trend) with the flatness of the regression function i.e. when the slope of the uncongested branch (in *(q,v)* coordinates) gets closer to zero. The high sensitivity of the estimate accuracy to the degree of flatness is due to the fact that the uncongested branch of the speed/flow diagrams often exhibits highly variable speeds, meaning that every value of flow has associated with it a relatively large range of vehicle speeds in free-flow.

C. Performance of speed variance / flow method

The flow trends obtained from the speed variance/flow regression are in general less accurate than the trends produced by the speed/flow regression, which can be traced back to the assumption of stationarity in 10 minutes time intervals. It must be noted that the assumption of stationarity is required for statistical significance of the variance value. Similarly, since several speed measurements are required to compute the speed variance, hence a flow estimate, the speed variance regression model cannot function on very refined time discretizations.

The accuracy of the speed variance regression estimate decreases with the flatness of the flow to speed function in the uncongested phase, similarly to the speed regression estimate. However, this decrease is less substantial than for the speed regression method, and in such cases the estimated flow using the speed variance regression is often more accurate than the estimated flow using the speed regression.

VI. Conclusions

This article proposed the analysis of the relation between point speed and flow. Performance assessment of different techniques for accurate conversion of point speeds to point flows was conducted, in the prospect of fusing speed data with conventional loop detectors.

The study used speed and flow measurements from September 2010, obtained from 112 NAVTEQ radars [1] deployed in the San Francisco Bay Area. The major steps of the analysis presented are the following:

- Evaluation and categorization of 112 measured speed/flow diagrams,
- Evaluation of 112 measured variance plots,
- Comparative benchmark of the speed variance to flow regression method with the speed to flow regression method.

The main conclusions of this study are the following.

The conventional speed/flow method is able to produce significantly more accurate results than the speed variance/flow method, in particular in the case of an increasing uncongested branch in *(q,v)* coordinates, which is not predicted by the theory. This accuracy deteriorates quickly however when the uncongested branch of the diagram in *(q,v)* coordinated becomes more flat.

The proposed speed variance/flow method does not achieve the accuracy obtained with the conventional method; this may be due to the assumption of stationarity, required for statistically significant computation of the speed variance. The proposed method, however, shows more accurate results than the traditional method in the case where the uncongested branch in *(q,v)* coordinates is relatively flat, which is a classical assumption on the free-flow phase.

The preliminary assessment proposed in this work shows promising results, with two methods with complementary behaviors providing reasonably accurate flow estimates. In particular, the evidence for traffic behaviors not well modeled by traffic theory and the characterization of the specific traffic episodes for which each method performs better lays the ground for more refined analytics. Further efforts on the topic encompass the use of a rigorous estimation setting for quantitative assessment of the proposed methods for specific applications.

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