IMPROVED VEHICLE LENGTH MEASUREMENT AND
CLASSIFICATION FROM FREEWAY DUAL-LOOP
DETECTORS IN CONGESTED TRAFFIC

THESIS

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ABSTRACT

Classified vehicle counts are a critical measure for forecasting the health of the roadway infrastructure and for planning future improvements to the transportation network. Balancing the cost of data collection with the fidelity of the measurements, length-based vehicle classification is one of the most common techniques used to collect classified vehicle counts. Typically the length-based vehicle classification process uses a pair of detectors to measure effective vehicle length. The calculation is simple and seems well defined. In particular, most conventional calculations assume that acceleration can be ignored. Unfortunately, at low speeds this assumption is invalid and performance degrades in congestion. As a result of this fact, many operating agencies are reluctant to deploy classification stations on roadways where traffic is frequently congested.

This thesis will first demonstrate that small changes in the calculations used in conventional practice can lead to large differences in performance during challenging conditions. This work considers seven different variations of vehicle length calculation, two of which perform much better than the others in congested freeway conditions down to 15 mph- both under theoretical vehicle motions and empirical data analysis. Then, to further improve performance, we evaluate the feasible range of true vehicle lengths that
could underlie a given combination of measured length, measured speed, and unobserved acceleration at dual-loop detectors. From this analysis we find that there are small uncertainty zones between length classes where the particular class is ambiguous. For the vehicles falling into the uncertainty zones we assign them to two or more classes-representing all of the feasible true length classes that could have yielded the measured speed and length. The rest of the length-speed plane can be unambiguously assigned to a single class. Finally, using empirical data these advances are shown to perform better than the current state of the practice, though we find that even the conventional method did surprisingly well in stop-and-go traffic for vehicle length calculation.

**Key words:**

Dual-loop detector; Speed and length measurement; Length-based vehicle classification; Freeway traffic; Congested traffic.
DEDICATION

This document is dedicated to my family and all the people that I love.
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I would like to express my deepest gratitude to my MS advisor, Prof. Benjamin Coifman, who has consistently provided guidance and support throughout my graduate study career. His immense knowledge, insightful research, and great patience have inspired and helped me to develop independent and creative thinking skills, which will benefit me throughout my entire life. Without his unwavering guidance, encouragement, and precision, this thesis would not have been possible.

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TABLE OF CONTENTS

ABSTRACT ........................................................................................................................................................................... ii
DEDICATION ........................................................................................................................................................................ iv
ACKNOWLEDGMENTS ................................................................................................................................................................. v
VITA .................................................................................................................................................................................................. vi
LIST OF TABLES .......................................................................................................................................................................... ix
LIST OF FIGURES .......................................................................................................................................................................... xi

CHAPTER 1 INTRODUCTION ....................................................................................................................................................... 1

CHAPTER 2 LENGTH MEASUREMENT METHODS ....................................................................................................................... 5
  2.1 CONVENTIONAL VEHICLE LENGTH MEASUREMENT - ZERO ACCELERATION METHOD .............................................. 5
  2.2 NEW METHOD - CONSTANT ACCELERATION METHOD ................................................................................................. 9

CHAPTER 3 LENGTH MEASUREMENT PERFORMANCE EVALUATION UNDER DIFFERENT VEHICLE MOTIONS .................................................................................................................. 12
  3.1 HYPOTHETICAL VEHICLE TRAJECTORIES ....................................................................................................................... 12
    3.1.1 CONSTANT SPEED MODEL ........................................................................................................................................ 13
    3.1.2 CONSTANT ACCELERATION MODEL .......................................................................................................................... 13
    3.1.3 NON-CONSTANT ACCELERATION MODEL ................................................................................................................ 18
    3.1.4 STOP MODEL ............................................................................................................................................................... 22
  3.2 EMPIRICAL VEHICLE DATA .................................................................................................................................................. 25
    3.2.1 NGSIM SYNTHESIS AND VALIDATION ....................................................................................................................... 26
    3.2.2 BHL VALIDATION .......................................................................................................................................................... 35
LIST OF TABLES

Table 3.1, Expressions of Seven Methods by Constant Acceleration Model.................................................................16

Table 3.2, Number of Vehicles in Each Measured Average Speed Bin by Method and Across the Entire NGSIM I-80,
population with absolute relative error in length ≤1%, ≤5%, and correctly classified at location 800 ft. ..................................................................................................................................................................................28

Table 3.3, Comparison of Three Methods: Nm, Cm+ and Cm for Vehicle Classification Accuracy Verification
using the NGSIM I-80 at location 800 ft. Where, 1, 2, 3 denote the vehicle length class: Class 1: LE ≤ 28 ft, Class 2: 28 ft < LE ≤ 46 ft, Class 3: LE > 46 ft. ..........................................................................................................................................................31

Table 3.4, Number of Vehicles in Each Measured Average Speed Bin by Method and Across the Entire NGSIM US-
101 Population with Absolute Relative Error in Length ≤1%, ≤5%, and Correctly Classified at Location 1000 ft. .........................................................................................................................................................32

Table 3.5, Comparison of Three Methods: Nm, Cm+ and Cm for Vehicle Classification Accuracy Verification
using the NGSIM US-101 at location 1000 ft. Where, 1, 2, 3 denote the vehicle length class: Class 1: LE ≤ 28 ft, Class 2: 28 ft < LE ≤ 46 ft, Class 3: LE > 46 ft. .........................................................................................................................................................34

Table 3.6, Number of Vehicles by BHL Data in Each Measured Average Speed Bin by Method and Across the Entire
Population with Absolute Relative Error in Length (a) ≤1%, (b) ≤5%.....................................................................................40

Table 3.7, Comparison of Three Methods: Nm, Cm+ and Cm for Vehicle Classification Accuracy Verification
using BHL data (left) and for the exact same vehicles the NGSIM synthetic data from NGSIM (right)....41

Table 4.1, The left-hand side of this table shows a comparison of the measured length-based vehicle class by
Cm+ when including the uncertainty zones against the true length-based vehicle class. The right-hand
side of this table repeats a comparison using only the constant speed boundaries between classes by
NGSIM I-80 data at location 1000 ft. ........................................................................................................59

table 4.2, using the real detector actuations from the BHL station, the left-hand side of this table shows a
comparison of the measured length-based vehicle class when including the uncertainty zones against the
true length-based vehicle class. the right-hand side of this table repeats a comparison using only the
constant speed boundaries between classes. ................................................................................................59

table C.1, vehicle motions distribution in each measured speed bin by NGSIM I-80 data at location 800 ft. .....78

table C.2, vehicle motions distribution in each measured speed bin by NGSIM US-101 data at location 1000
ft........................................................................................................................................................78

Table D.1, the left-hand side of this table shows a comparison of the measured length-based vehicle class by
NM when including the uncertainty zones against the true length-based vehicle class. the right-hand
side of this table repeats a comparison using only the constant speed boundaries between classes by
NGSIM I-80 data at location 1000 ft. ........................................................................................................86

Table D.2, using the real detector actuations from the BHL loop detector station at 221 ft, the left-hand side
of this table shows a comparison of the measured length-based vehicle class when including the
uncertainty zones against the true length-based vehicle class. the right-hand side of this table repeats a
comparison using only the conventional constant speed boundaries between classes. ........................86
LIST OF FIGURES

FIGURE 2.1, (A) SCHEMATIC OF A VEHICLE PASSING OVER A DUAL-LOOP DETECTOR, (B) THE TIME SERIES RESPONSE OF THE TWO DETECTORS AND THE RESULTING MEASUREMENTS USED TO CALCULATE SPEED AND LENGTH. ................................. 7

FIGURE 3.1, VEHICLE CONSTANT ACCELERATION MODEL ........................................................................................................................................ 14

FIGURE 3.2, FAMILY DIAGRAM OF RELATIVE ERROR IN LENGTH, L_e, VERSUS INITIAL SPEED, V_0, FOR THE SEVEN METHODS UNDER THE CONSTANT ACCELERATION MODEL WITH (A) A>0, AND (B) A<0. L_e IS CONSTANT IN A GIVEN COLUMN OF SUBPLOTS, BUT INCREASES FROM LEFT TO RIGHT, WHILE V_0 IS CONSTANT IN A GIVEN ROW OF SUBPLOTS, INCREASING FROM TOP TO BOTTOM. .......................................................................................................................... 17

FIGURE 3.3, (A) TIME SERIES SPEED OF AN INDIVIDUAL VEHICLE FOR THE NON-CONSTANT ACCELERATION MODEL, (B) TIME SERIES SPEED OF INDIVIDUAL VEHICLE FOR THE STOP MODEL ........................................................................................................ 19

FIGURE 3.4, FAMILY DIAGRAM OF ABSOLUTE RELATIVE ERROR IN LENGTH, L_e, VERSUS INITIAL SPEED, V_0, FOR THE SEVEN METHODS UNDER THE NON-CONSTANT ACCELERATION MODEL WITH (A) A>0, AND A_k<0, (B) A_k<0, AND A_j>0. L_e IS CONSTANT IN A GIVEN COLUMN OF SUBPLOTS, BUT INCREASES FROM LEFT TO RIGHT, WHILE V_0 IS CONSTANT IN A GIVEN ROW OF SUBPLOTS, INCREASING FROM TOP TO BOTTOM .................................................................................................................. 21

FIGURE 3.5, FAMILY DIAGRAM OF ABSOLUTE RELATIVE ERROR IN LENGTH, L_e, VERSUS INITIAL SPEED, V_0, FOR THE SEVEN METHODS UNDER THE STOP MODEL WITH A_k<0, A_j>0 AND (A) ΔT = 0 SEC, (B) ΔT = 1 SEC, (C) ΔT = 5 SEC. L_e IS CONSTANT IN A GIVEN COLUMN OF SUBPLOTS, BUT INCREASES FROM LEFT TO RIGHT, WHILE V_0 IS CONSTANT IN A GIVEN ROW OF SUBPLOTS, INCREASING FROM TOP TO BOTTOM ................................................................................................................ 23

FIGURE 3.6, PERCENTAGE OF VEHICLES IN EACH MEASURED AVERAGE SPEED BIN BY METHOD WITH ABSOLUTE RELATIVE ERROR IN LENGTH FOR NGSIM I-80 (A) ≤1%, (B) ≤5% AT LOCATION 800 FT. .................................................................................................................. 29
Figure 3.7, Percentage of vehicles in each measured average speed bin by method with absolute relative error in length for NGSIM US-101 (a) ≤1%, (b) ≤5% at location 1000 ft. ......................................................... 33

Figure 3.8, Measured effective length versus true effective vehicle length from (a) NM on the BHL loop detector data, (b) CM+ on the BHL loop detector data, (c) CM on the BHL loop detector data, (d) NM on the NGSIM synthetic detector data, (e) CM+ on the NGSIM synthetic detector data, and (f) CM on the NGSIM synthetic detector data. All six subplots use the same exact set of passing vehicles. .......................... 38

Figure 3.9, (a) CDF of length error using BHL data, (b) CDF of absolute length error using BHL data. ............ 39

Figure 4.1, Acceleration distribution of all vehicles of NGSIM I-80 data. ......................................................... 46

Figure 4.2, (a) Vehicle classification for constant speed model, (b) Vehicle classification for constant acceleration model, (c) Vehicle classification for non-constant acceleration model, and (d) Vehicle classification for stop model. ........................................................................ 48

Figure 4.3, Theoretical vehicle classification plane by CM+ with acceleration equal to (a) +/-1 MPHPS, (b) +/-2 MPHPS, (c) +/-4 MPHPS. ........................................................................................................... 54

Figure 4.4, The length-based vehicle classification plane by CM+ showing the uncertainty zones where errors in the measured length could lead to a misclassification; the numbers on this plot denote the vehicle class/classes that fall within the given area. ...................................................................................... 55

Figure 4.5, (a) Scatter plot by CM+ comparing the measured versus true NGSIM length-based vehicle classification at the study location, (b) CDF of average measured speeds for the same vehicles by NGSIM I-80 at 1000 ft. .................................................................................................................. 57

Figure 4.6, (a) Vehicle classification by CM+ using measured effective vehicle length versus measured speed for all of the NGSIM data, (b) repeating part A, but only showing the misclassifications that do fall outside of the correct region or uncertainty zones by NGSIM I-80 at 1000 ft ...................................................... 59

Figure 4.7, (a) Scatter plot by CM+ comparing the measured versus true NGSIM length-based vehicle classification for BHL data of station 8, (b) CDF of average measured speeds for the same vehicles. ...... 60

xii
FIGURE 4.8, (a) Vehicle classification by CM+ using measured effective vehicle length versus measured speed for BHL data of station 8, (b) misclassifications using measured effective vehicle length versus measured speed. ........................................................................................................................................61

FIGURE B.1, Schematic of a vehicle passing over a dual-loop detector. .......................................................................................................................76

FIGURE B.2, Family diagram of absolute relative error in length, Le, versus stop location (e.g., distance AO), for the seven methods under the stop model with \( a<0, a>_0 \) and \( \Delta t = 0 \) sec. Le is constant in a given column of subplots, but increases from left to right, while \( V_0 \) is constant in a given row of subplots, increasing from top to bottom refer to figure 3.5a. ........................................................................................................................................76

FIGURE D.1, (a) Vehicle classification for constant speed model by NM, (b) vehicle classification for constant acceleration model by NM \( (a = +2 \text{ mphps}) \), (c) vehicle classification for non-constant acceleration model by NM \( (4 \text{ different combinations of } a_0 \text{ and } a_1 \text{ shown}) \), (d) vehicle classification for stop model by NM \( (a_1 = -2 \text{ mphps}, a_1 = +2 \text{ mphps}) \). ........................................................................................................................................79

FIGURE D.2, Theoretical vehicle classification plane by NM with acceleration equal to (a) +/-1 mphps, (b) +/-2 mphps, (c) +/-4 mphps. ........................................................................................................................................80

FIGURE D.3, The length-based vehicle classification plane by NM showing the uncertainty zones where errors in the measured length could lead to a misclassification; the numbers on this plot denote the vehicle class/classes that fall within the given area. ........................................................................................................................................82

FIGURE D.4, Scatter plot by NM comparing the measured versus true NGSIM length-based vehicle classification at the study location, (b) CDF of average measured speeds for the same vehicles by NGSIM I-80 data at location 1000 ft. ........................................................................................................................................83

FIGURE D.5, Vehicle classification by NM using measured effective vehicle length versus measured speed by NGSIM I-80 data at location 1000 ft. ........................................................................................................................................84

FIGURE D.6, (a) Scatter plot by NM comparing the measured versus true NGSIM length-based vehicle classification for BHL data of station 8, (b) CDF of average measured speeds for the same vehicles. ......84

xiii
Figure D.7, (a) Vehicle classification by NM using measured effective vehicle length versus measured speed for BHL data of station 8. (b) Repeating part a, but only showing the misclassifications that do fall outside of the correct region or uncertainty zones.
CHAPTER 1

INTRODUCTION

Vehicle classification is an important traffic parameter for transportation planning and infrastructure management. Length-based vehicle classification from dual-detector is among the lowest cost technologies commonly used for collecting these data, e.g., the USDOT mandates that all states collect these classification data. Balancing the cost of data collection with the fidelity of the measurements, length-based vehicle classification is one of the most common techniques used to collect classified vehicle counts. Typically the length-based vehicle classification process uses a pair of detectors (e.g., dual-loop detectors) or a pair of detection zones (e.g., Wavetronix SmartSensor) to measure traversal time and then converts the traversal time to speed by taking the quotient of the known distance between the detection zones. The product of this speed measurement and the dwell time over one or both detectors is then used to calculate the effective vehicle length. While the calculation is simple and seems well defined, this thesis will soon demonstrate that small changes in the calculations can lead to large differences in
performance during challenging conditions. In particular, most conventional calculations assume that acceleration can be ignored, which simply is not the case in congested traffic.

In recent years there have been some empirical studies that have looked at the accuracy of individual vehicle measurements, e.g., [1-3], but there have been very few recent studies that have contemplated the nuances of the calculations as we do herein, e.g., at low speeds the negligible acceleration assumption is invalid (as shown in Section 3.1) and performance degrades significantly in congestion [12]. Although the focus of the current work is on length-based classification, the same speed measurement techniques are commonly employed at axle based classification stations and this work should apply there as well.

In this thesis, first, we present six variations of the conventional vehicle length measurement and one new approach for measuring effective vehicle length. Next, we evaluate the seven different variations of vehicle length calculation under theoretical vehicle motions and then using empirical data. Two of the approaches performed much better than the rest in extreme conditions on freeways for speeds down to 15 mph.

Second, using these two top performing approaches, we evaluate the feasible range of true vehicle lengths that could underlie a given combination of measured length, measured speed, and unobserved acceleration at a dual-loop detector. We find that there are small uncertainty zones between the distinct length classes, where the given vehicle's true class is ambiguous. These uncertainty zones remain fairly small down to about 10 mph and then grow exponentially down to about 5 mph. By mapping these uncertainty zones, most vehicles can be accurately sorted to a single length-class, e.g., a three bin
scheme might seek to sort passenger vehicles, single unit trucks, and multiple unit trucks into different bins, while a few vehicles that fall within the zones are assigned to two or more classes (corresponding to the range of true lengths that could have resulted in the specific measurement). Using empirical data from stop-and-go traffic we find that the conventional approach does surprisingly well; however, our new approach does even better, reducing the classification error rate due to acceleration by at least a factor of five relative to the conventional method. Meanwhile, our approach still assigns over 98% of the vehicles to a single class.

The remainder of this thesis is structured as follows: Chapter 2 develops the seven length measurement methods. Chapter 3 evaluates the performance of the seven methods under different hypothetical vehicle motions, and then uses empirically collected vehicle trajectories and actual dual-loop detector measurements to evaluate the performance of the seven methods in stop-and-go traffic. We found two of the length measurement methods perform much better than the other five under the most challenging conditions, and these two methods are used exclusively through the remainder of the thesis. Chapter 4 evaluates the impacts of acceleration and complete stops on the length measurements, identifying the pairwise combinations of measured-length and measured-speed (both measurable at a dual-loop detector) to identify the uncertainty zones where the measured length could result in a different classification that the true vehicle length. Measurements that fall in these zones are assigned to either two or three possible vehicle classes (representing the range of feasible true vehicle lengths that could have resulted in the measured vehicle length). Then we use the new classification method with uncertainty
zones to classify empirical data, and discuss the implications. Finally, in Chapter 5 the thesis closes with a discussion and conclusions.
CHAPTER 2

LENGTH MEASUREMENT METHODS

This section presents the seven different vehicle length calculations evaluated in this study.

2.1 Conventional Vehicle Length Measurement - Zero Acceleration Method

The conventional length measurement process is not precisely defined. This ambiguity arises from the redundancy of the dual-loop detector, and from the fact that the measurements occur over space, as illustrated in Figure 2.1. There are two detectors separated by spacing S (leading edge to leading edge). A passing vehicle first crosses detector #1, with the resulting pulse from $t_1$ to $t_2$ in the bivalent output shown in Figure 2.1b, and then detector #2, with the resulting pulse from $t_3$ to $t_4$. The dual-loop detector yields two separate measures of traversal time, one from the rising edges of the two pulses: $TT_r = t_3 - t_1$; and one from the falling edges: $TT_f = t_4 - t_2$, which in turn yield
two separate measures of speed, \( V_r = \frac{S}{TT_r} \) and \( V_f = \frac{S}{TT_f} \). Similarly, there are two separate measures of dwell time for the passing vehicle, \( T_u = t_2 - t_1 \) from detector #1 and \( T_d = t_4 - t_3 \) from detector #2. When the vehicle traverses the dual-loop detectors at a constant speed, then in the absence of detector errors the two speeds will be equal and similarly the two dwell times will be equal. Because the two detectors are separated by \( S \) and the vehicle has an effective length, \( L_e \) (the sum of the physical vehicle length and detection zone size), these temporal measurements also have a spatial component. Thus, any change in speed will distort the individual speed measurements and dwell times, which in turn will usually cause the redundant measurements to differ in value. Generally at free flow speed the impacts from acceleration are negligible, thus the error caused from the redundancy of the dual-loop detector, and over space measurement is very small. However, at lower speeds the potential difference becomes significant and ultimately it is intractable if the vehicle comes to a complete stop while traversing the dual-loop detectors.
Figure 2.1, (a) Schematic of a vehicle passing over a dual-loop detector, (b) the time series response of the two detectors and the resulting measurements used to calculate speed and length.

In conventional practice speed is usually measured assuming acceleration is zero. Formalizing this conventional method, CM, there are two possible length measurements, defined by Equation 1a and b. Typically an operating agency would only use only one of the two terms from Equation 1, e.g., some Caltrans engineers have expressed a preference for 1a because they feel \( V_r \) tends to be measured more accurately than \( V_f \) by dual-loop detectors.

\[
L_{CMr} = V_r \times T_u \tag{1a}
\]

\[
L_{CMf} = V_f \times T_d \tag{1b}
\]
The form of these equations is important. Figure 2.1 shows that \( V_r \) and \( T_u \) are measured roughly concurrently, and similarly \( V_f \) and \( T_d \) are measured roughly concurrently. So in general the paired speed and dwell time should be impacted similarly (but not identically) by any change in speed while the vehicle traverses the dual-loop detector. So we consider swapping the pairing of Equation 1, and we term as CM-defined in Equation 2. While similar in form to Equation 1, now the time period where speed is measured does not overlap the period that the dwell time measured and thus, eliminates any benefits of the overlapping measurement period.

\[
L_{CM-r} = V_r \times T_d \\
L_{CM-f} = V_f \times T_u
\] (2a, 2b)

To address measurement noise, [5] used both forms of Equation 1 and calculated the arithmetic average of the two terms [5]. In the present work we call this arithmetic average CM+, as per Equation 3.

\[
L_{CM+} = \frac{V_r \times T_u + V_f \times T_d}{2} = \text{Av}(L_{CM})
\] (3)

WSDOT (the Washington State Department of Transportation) used the product of rising edge speed \( V_r \), and the arithmetic average of \( T_u \) and \( T_d \) to measure the effective vehicle length [6] (effectively an arithmetic average of Equations 1a and 2a). After that,
[7] extended the WSDOT algorithm to instead use the arithmetic average of $V_r$ and $V_f$ via Equation 4, which we term CMO.

\[ L_{\text{CMO}} = \frac{V_r + V_f}{2} \times \frac{T_u + T_d}{2} = \text{Av}(V) \times \text{Av}(T) \]  \hspace{1cm} (4)

Next, for completeness we consider two different averages that we have not found in the literature. First, the product of the harmonic average speed (which is proportional to the inverse of the arithmetic average traversal time) and the arithmetic average dwell time via Equation 5, which we term CMX. Second, we find the product of the harmonic average speed and harmonic average dwell time via Equation 6, which we term CMY.

\[ L_{\text{CMX}} = \frac{S}{T_{Tr} + T_{Tf}} \times (T_u + T_d) = \text{Hav}(V) \times \text{Av}(T) \]  \hspace{1cm} (5)

\[ L_{\text{CMY}} = \frac{2S}{T_{Tr} + T_{Tf}} \times \frac{2}{\frac{1}{T_u} + \frac{1}{T_d}} = \text{Hav}(V) \times \text{Hav}(T) \]  \hspace{1cm} (6)

2.2 New Method - Constant Acceleration Method

All six of the conventional method variants assume that acceleration can be ignored, they only differ in the way they average speed and dwell time. They should all yield the same value when a vehicle's acceleration is negligible as it traverses the dual-loop detector. As we will show in Chapter 3, when the vehicle's speed changes as it traverses the dual-loop detector, the performance of these six methods varies greatly. To lessen these impacts, we sought to revisit the equations of motion and derive a more
sophisticated method to calculate speed, length and taking acceleration into consideration using the four transition-times, \( t_1 \) to \( t_4 \), from Figure 2.1b assuming that acceleration is constant as the vehicle traverses the dual-loop detector. Obviously, at low speeds even the assumption of constant acceleration breaks down, and the next chapter will explicitly evaluate those cases.

This new method, termed as NM, accounts for the impacts of initial speed, \( V_0 \), and constant acceleration, \( a \), on the four transition-time measurements to calculate \( L_{NM} \). The net result are three Equations (7-9) and three unknowns, \( V_0 \), \( a \), and \( L_{NM} \), as follows,

\[
S = V_0 * TT_f + \frac{1}{2} a * TT_f^2
\]  
(7)

\[
L_{NM} = V_0 * T_u + \frac{1}{2} a * T_u^2
\]  
(8)

\[
S + L_{NM} = V_0 * (T_u + TT_f) + \frac{1}{2} a * (T_u + TT_f)^2
\]  
(9)

Manipulating these equations, Equations 10-12 solve for the three unknown variables in terms of the measurements from the dual-loop detector (Figure 2.1).

\[
a = \frac{2(V_r-V_f)}{(T_u+T_d)}
\]  
(10)

\[
V_0 = \frac{(T_u+T_d)(S-(V_r-V_f)TT_f^2)}{(T_u+T_d)TT_f}
\]  
(11)

\[
L_{NM} = S * \frac{(TT_r+TT_f)T_d*T_u}{(T_u+T_d)*TT_r*TT_f} = \frac{V_r+V_f}{2} * \frac{2}{1/T_u+1/T_d} = Av(V) * Hav(T)
\]  
(12)
The constant acceleration assumption was also used in [8-9], yielding a measurement equivalent to Equation 12. Although length is equivalent, [8-9] measure speed differently and do not measure acceleration. It appears that this constant acceleration idea has largely been forgotten, though the idea occasionally reappears in the literature, e.g., [10].
CHAPTER 3

LENGTH MEASUREMENT PERFORMANCE EVALUATION
UNDER DIFFERENT VEHICLE MOTIONS

This chapter evaluates the seven different vehicle length measurement methods from the previous chapter, first by using hypothetical vehicle motion models, and then by applying the methods to empirical data. Finally this chapter closes with a discussion practical considerations.

3.1 Hypothetical Vehicle Trajectories

For this section we model vehicle motion using four different models: constant speed, constant acceleration, non-constant acceleration, and stop model, as discussed below. Using a given vehicle motion model, we then simulate the vehicle trajectory and synthesize the resulting dual-loop detector interval times (i.e., $T_u$, $T_d$, $TT_r$, and $TT_f$ in Figure 2.1) as a function of a passing vehicle's true effective length, $L_e$, initial speed, $V_0$, acceleration (if any), and dual-loop detector spacing, $S$. These detector measurements are
used to calculate the measured effective vehicle length, \( L \), using each of the seven length measurement methods. The \( L \) measurements are compared to \( L_e \) to find the resulting error.

To avoid confounding factors the detector measurements are synthesized without any measurement errors (this assumption is eventually relaxed in Section 3.2.2). So the results in this section represent strictly the impacts of the assumptions in the given measurement method and the resulting biases from the implementation.

### 3.1.1 Constant Speed Model

The simplest vehicle motion is the constant speed model, whereby the vehicle passes a dual-loop detector with a constant speed. In this case, there is no acceleration and the vehicle does not stop while traversing the detector, thus \( V_r = V_f \), \( T_{Tr} = T_{Tf} \) and \( T_u = T_d \). In this case all seven of the length measurement methods will yield the same measured effective vehicle length for a given vehicle, and do so without any errors. This result should not be surprising since the six conventional methods implicitly assume that vehicles pass with a constant speed, and the acceleration from Equation 10 of the new method is equal to zero in this model.

### 3.1.2 Constant Acceleration Model

Of course vehicles do not travel at constant speeds for their entire trip. The impacts of a given acceleration rate increase as the initial speed decreases since the slower the
speed the longer the time period during which acceleration will impact a given vehicle's trajectory as the vehicle passes a dual-loop detector. The simplest vehicle motion that includes acceleration is one of constant acceleration, with no stops over the dual-loop detector. Given constant acceleration, $a$, initial speed $V_0$, true vehicle effective vehicle length $L_e$, and dual-loop detector spacing $S$, then the time series speed is shown in Figure 3.1 and the resulting interval times are given by Equations 13-16 and enumerated in Table 3.1 for each of the seven length measurement methods.

![Figure 3.1, Vehicle Constant Acceleration Model](image)

$$V_0 \times TT_r + \frac{1}{2} a \times TT_r^2 = S \rightarrow$$

$$TT_r = \frac{-V_0 + \sqrt{V_0^2 + 2aS}}{a} \quad (13)$$

$$L_e = V_0 \times T_0 + \frac{1}{2} a \times T_u^2 \rightarrow$$

$$T_u = \frac{-V_0 + \sqrt{V_0^2 + 2aL_e}}{a} \quad (14)$$
\[ L_e + S = V_0^* (T_d + TT_f) + \frac{1}{2} a^* (T_d + TT_f)^2 \rightarrow \]

\[ T_d = \frac{\sqrt{V_0^2 + 2a^*(L_e + S)} - \sqrt{V_0^2 + 2a^*S}}{a} \]  

(15)

\[ TT_f = TT_r + T_d - T_u \rightarrow \]

\[ TT_f = \frac{\sqrt{V_0^2 + 2a^*(L_e + S)} - \sqrt{V_0^2 + 2a^*L_e}}{a} \]  

(16)

We synthesized a range of: a, \( V_0 \), \( L_e \), found the interval-times and then used these to measure \( L \) from all seven methods. In this case the assumptions of the conventional methods differ from the actual vehicle-motion and as expected, length measurement errors occurred. While the NM implicitly assumes a constant acceleration, indeed, in this case we find that NM is always the most accurate \( L \), without any error (as shown in the last row of Table 3.1). Of greater interest is the fact that the six conventional methods exhibit a range of performance, with some markedly better than others. Figure 3.2a and b show the relative error in length via Equation 17 from all seven methods as a function of \( V_0 \) given four different values of a (one per row of subplots) and four different values of \( L_e \) (one per column of subplots). Both CM and CM- yield two different \( L \) per vehicle, to facilitate readability we only show one measurement from the given method (i.e., from Equations 1a and 2a).
<table>
<thead>
<tr>
<th>Method</th>
<th>Expression using constant acceleration model</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM</td>
<td>( L_{CM} = V_f \cdot T_u = S \cdot \frac{-V_o+\sqrt{V_o^2+2a+L_e}}{-V_o+\sqrt{V_o^2+2a+S}} )</td>
</tr>
<tr>
<td>CM-f</td>
<td>( L_{CM-f} = V_f \cdot T_d = S \cdot \frac{\sqrt{V_o^2+2a+(L_e+S)}-\sqrt{V_o^2+2a+S}}{-V_o+\sqrt{V_o^2+2a+S}} )</td>
</tr>
<tr>
<td>CM-</td>
<td>( L_{CM} = V_f \cdot T_u = S \cdot \frac{-V_o+\sqrt{V_o^2+2a+L_e}}{-V_o+\sqrt{V_o^2+2a+S}} )</td>
</tr>
<tr>
<td>CM</td>
<td>( L_{CM} = \frac{V_f \cdot T_u+V_f \cdot T_d}{2} = S \cdot \frac{-V_o+\sqrt{V_o^2+2a+L_e}}{2} + \frac{\sqrt{V_o^2+2a+(L_e+S)}-\sqrt{V_o^2+2a+S}}{-V_o+\sqrt{V_o^2+2a+S}} )</td>
</tr>
<tr>
<td>CMO</td>
<td>( L_{CMO} = \frac{V_f + V_f}{2} = \frac{S \cdot (-V_o+\sqrt{V_o^2+2a+L_e}) + \sqrt{V_o^2+2a+(L_e+S)}-\sqrt{V_o^2+2a+S}}{-V_o+\sqrt{V_o^2+2a+S}} )</td>
</tr>
<tr>
<td>CMX</td>
<td>( L_{CMX} = S \cdot \frac{(T_u + T_d)}{Tr+Tf} = \frac{S \cdot (-V_o+\sqrt{V_o^2+2a+L_e}) + \sqrt{V_o^2+2a+(L_e+S)}-\sqrt{V_o^2+2a+S}}{-V_o+\sqrt{V_o^2+2a+L_e}} )</td>
</tr>
<tr>
<td>CMY</td>
<td>( L_{CMY} = \frac{2S}{Tr+Tf} \cdot \frac{a}{T_u+T_d} = \frac{a}{4} )</td>
</tr>
<tr>
<td>NM</td>
<td>( L_{NM} = S \cdot \frac{(T_u+T_d)+T_d}{(T_u+T_d)+T_d+T_d} = \frac{S \cdot (-V_o+\sqrt{V_o^2+2a+L_e}) + \sqrt{V_o^2+2a+(L_e+S)}-\sqrt{V_o^2+2a+S}}{-V_o+\sqrt{V_o^2+2a+L_e}} )</td>
</tr>
</tbody>
</table>

16
Figure 3.2, Family diagram of relative error in length, $L_c$, versus initial speed, $V_0$, for the seven methods under the constant acceleration model with (a) $a>0$, and (b) $a<0$. $L_c$ is constant in a given column of subplots, but increases from left to right, while $V_0$ is constant in a given row of subplots, increasing from top to bottom.
relative error in length = \( \frac{L_{\text{measured}} - L_e}{L_e} \times 100\% \)  \hspace{1cm} (17)

As one might expect, across all of the conventional methods the magnitude of the errors generally increases with \( a \), \( L_e \), and the inverse of \( V_0 \). Note that in many of the subplots of both Figure 3.2a and b the curve for CM- and sometimes even CM fall completely beyond the 5% boundaries used in the given subplot. As noted above NM has no error given a constant acceleration. The next best method is CM+, the only conventional method that maintained an absolute error below 5% on almost all of the cases (215 cases with error ratio lower than 5% out of total 224 cases). For the shortest \( L_e \) in both figures 3.2a and b the next three best methods are in this order: CMX, CMY, CMO. For the longer values of \( L_e \) the order changes to CMO, CMX, CMY. In any event CM- offers the worst performance, followed by CM. The averaging methods perform better than CM because the impacts of acceleration on the different interval times can cancel one another out, something that does not occur with CM and the situation is exasperated with CM- where the two interval times do not overlap at all.

3.1.3 Non-constant Acceleration Model

The more time a driver spends over a dual-loop detector (both due to \( L_e \) and \( V_0 \)) the greater the opportunity for the driver to change the acceleration rate. While the possibilities are literally infinite, we use a piecewise constant acceleration model, as shown in Figure 3.3a, to represent a general case of non-constant acceleration. This
model is characterized by two different accelerations, \(a_i\) and \(a_j\); initial speed \(V_0\); the speed at the inflection point \(V_x\); and the effective vehicle length \(L_e\). In the context of Figure 2.1, if we assume that the start time \(t_i = 0\) for a vehicle passing a dual-loop detector, the corresponding end time is \(t_4 = t_i + t_j\), where \(t_i\) and \(t_j\) are defined in Equations 18-19. The calculation process of the other two timestamps \(t_2\) and \(t_3\) is shown in Appendix A. Then based on the four transitions, the time intervals, measured speed, acceleration and vehicle length etc. can be obtained subsequently.

\[
t_i = \frac{V_x - V_0}{a_i}
\]

(18)

\[
t_j = \frac{-V_x + \sqrt{V_x^2 - 2a_j((V_x^2 - V_0^2)/2a_i - S - L_e)}}{a_j}
\]

(19)

Figure 3.3, (a) Time series speed of an individual vehicle for the non-constant acceleration model, (b) time series speed of individual vehicle for the stop model.
Once more we synthesized a range of: \(a, V_0, L_e\), found the interval-times and then used these to measure \(L\) from all seven methods. Under the non-constant acceleration model the assumptions of all seven of the length measurement methods differ from the actual vehicle-motion and the exhaustive set of all possible combinations of parameters becomes difficult to present. Figure 3.4a and b show two representative examples, presenting the absolute relative error via Equation 20 from all seven methods as a function of \(V_0\) given four different sets of \(a_i\) and \(a_j\) (one set per row of subplots) and four different values of \(L_e\) (one per column of subplots). In Figure 3.4a and b the magnitude of \(a_i\) and \(a_j\) are equal, but they are opposite in sign. So here the vehicle accelerates for exactly half of the time it is over the dual-loop detector and then decelerates for the second half of the time. Within a given subplot \(V_X, t_i\) and \(t_j\) are constant for a given \(V_0\), but these values vary with \(V_0\) and they differ from one subplot to the next due to the independent \(L_e, V_0\), and \(|a_i|\).

\[
\text{absolute relative error in length} = \frac{|L_{\text{measured}} - L_e|}{L_e} \times 100\% \tag{20}
\]

In this case there is no single "best" method. There is a cluster of NM, CM+, CMX and CMY offering similar performance with the lowest errors. For the shortest \(L_e\) CMY (figure 3.4a) or CM+ (figure 3.4b) exhibits the best performance, followed by NM and then CMX; for longer values of \(L_e\), NM tends to do slightly better than the rest, followed by CM+, CMY and CMX. After this cluster comes CM, then CMO, and finally CM-(though sometimes CMO pulls ahead of CM).
Figure 3.4, Family diagram of absolute relative error in length, $L_{CV}$ versus initial speed, $V_0$, for the seven methods under the non-constant acceleration model with (a) $a_i > 0$, and $a_j < 0$, (b) $a_i < 0$, and $a_j > 0$. $L_c$ is constant in a given column of subplots, but increases from left to right, while $V_0$ is constant in a given row of subplots, increasing from top to bottom.
3.1.4 Stop Model

In heavy congestion traffic often comes to a complete stop. This situation is the most challenging for length measurement. Short vehicles can stop between the two detection zones, in which case the low speed will be reflected in the speed measurements but not the dwell times. On the other hand, long vehicles can stop over both detectors, so the low speed will be reflected in the dwell times but not the measured speed since \( V_f \) is measured strictly before the stop and \( V_f \) strictly after the stop.

We developed the stop model to capture this situation, as follows. A given vehicle with \( L_e \) and \( V_0 \) will traverse a dual-loop detector until coming to a stop with a constant, negative acceleration rate \( a_i \), for a period \( t_i \), remain stopped for some time \( \Delta t \), and then depart with a constant, positive acceleration rate \( a_j \), for a period \( t_j \) until completely past the dual-loop detector, as shown in Figure 3.3b. We synthesized a range of \( a, V_0, L_e \), found the interval times and then used these to measure length from all seven methods. As with the non-constant acceleration model the assumptions of all seven of the length measurement methods differ from the actual vehicle motion.

Figure 3.5a, b and c show three representative examples, presenting the absolute relative error from all seven methods as a function of \( V_0 \) given four different sets of \( a_i \) and \( a_j \) (one set per row of subplots) and four different values of \( L_e \) (one per column of subplots) with different stop time for each figure (note that the horizontal scale changes from subplot to subplot to show detail). Again the example shows the case when the magnitude of \( a_i \) and \( a_j \) are equal, but opposite in sign. Through the three plots with \( \Delta t = 0 \)
sec / 1 sec / 5 sec respectively. Recognizing the fact that any non-zero stop time can only degrade performance beyond the zero stop time case, \( \Delta t = 0 \) is the best case scenario then followed by \( \Delta t = 1 \) sec and finally \( \Delta t = 5 \) sec.

(Figure 3.5 Continued)

Figure 3.5, Family diagram of absolute relative error in length, \( L_c \), versus initial speed, \( V_0 \), for the seven methods under the stop model with \( a_r < 0 \), \( a_r > 0 \) and (a) \( \Delta t = 0 \) sec, (b) \( \Delta t = 1 \) sec, (c) \( \Delta t = 5 \) sec. \( L_c \) is constant in a given column of subplots, but increases from left to right, while \( V_0 \) is constant in a given row of subplots, increasing from top to bottom.
In Figure 3.5 we see that all of the scenarios exhibit a peak error at a different value of $V_0$. The peak error corresponds to the case when a short vehicle stops completely.
between the two detectors or a long vehicle stops over both of the detectors. The distance to a stop varies based on $a_i$ and $V_0$ as the vehicle first enters the dual-loop detector, so as $a_i$ changes for a given $V_0$, it should not be surprising that the worst performance seemingly moves around different values of $V_0$. This shifting simply reflects the interrelationship of the various parameters. When the vehicle stops in the worst possible location, i.e., the middle of the dual-loop detector (refer to Appendix B) for all methods except CM-, the six methods have errors in excess of 40% for all 16 scenarios presented. Away from this peak error, NM usually offers the best performance followed by CM+. The remaining five methods generally exhibit errors in excess of 10% or larger throughout the range of $V_0$ associated with the stopping vehicle.

3.2 Empirical Vehicle Data

The previous section relied strictly on assumed models of motion, now we consider performance from empirical data without any presumed motion. Here, we employ the Next Generation Simulation (NGSIM) datasets. The NGSIM program was initiated by the Federal Highway Administration to collect high-quality, empirical vehicle trajectory data to support the development of better traffic simulation [11]. To validate our work, first we use the I-80 dataset, which includes vehicle trajectories over approximately 1/3 mi of I-80 in Emeryville, California for 45 min during rush-hour on April 13, 2005, then we use the US-101 dataset, which includes vehicle trajectories over a similar distance of US-101 in Los Angeles, California for 45 min during rush-hour on June 15, 2005.
3.2.1 NGSIM synthesis and validation

The NGSIM data include instantaneous speed and location for every passing vehicle as well as the vehicle's physical length. We simulated a dual-loop detector in each lane, located a fixed distance past the entry point (800 ft for I-80 data, and 1,000 ft for US-101). The detection zone size was set to 6 ft, with $S = 20$ ft. The synthesized transition-times $t_1$ and $t_3$ come directly from the NGSIM trajectory data as the vehicle passes the leading edge of each simulated loop detector. The trajectories are linearly interpolated to find the exact passage time because the raw NGSIM data are sampled at 10 Hz, which is too slow to calculate accurate vehicle lengths. Transition-times $t_2$ and $t_4$ come from a given vehicle's trajectory shifted upstream in space by the vehicle's length and the size of the detection zone. These four synthetic transition-times are then used to measure $L$ from all seven methods, while $L_e$ comes from the recorded NGSIM vehicle length plus the size of the detection zone.

The seven length measurement methods are first evaluated using the entire NGSIM I-80 dataset, i.e., all of the available 45 min from each of 6 lanes. The arithmetic average, $\bar{v}$, of $V_r$ and $V_f$ as in equation 21 is used to sort the results into bins by 5 mph from 0 to 30 mph and by 10 mph when higher than 30 mph. The top part of Table 3.2 shows the total number of vehicles falling into each speed bin and then for each of the seven methods, reports the number of those vehicles that had an absolute relative length measurement error below 1%. Figure 3.6a shows these same results as a percent of the total number of vehicles in each speed bin. NM and CM+ show the best performance overall, with CM+ dropping below NM in the highest speed bin (a difference of $2/36$
vehicles). Both CM+ and NM had over 90% of the length measurements within 1% absolute relative error in every speed bin except for the low speed bins below 10 mph. This process is repeated in the bottom part of Table 3.2 and Figure 3.6b tallying those vehicles with measurement error below 5%. The results are similar to the 1% threshold, though now NM and CM+ are above 85% for even the lowest speed bin and above 99% for all speed bins above 10 mph. Figure 3.6a-b also show that performance is already very good using CM for this dataset with well-tuned detectors, suggesting that the extreme accelerations in the lower portions of Figures 3.2 and 3.4, as well as the worst case stop locations of Figure 3.5 are fairly uncommon.
Table 3.2. Number of vehicles in each measured average speed bin by method and across the entire NGSIM I-80 population with absolute relative error in length ≤1%, ≤5%, and correctly classified at location 800 ft.

<table>
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<td>Total</td>
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<tr>
<td>CM</td>
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<td>416</td>
<td>1,162</td>
<td>1,238</td>
<td>808</td>
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<td>421</td>
<td>171</td>
<td>33</td>
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<td>370</td>
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<td>197</td>
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<td>1,352</td>
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<td>439</td>
<td>459</td>
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<td>446</td>
<td>180</td>
<td>33</td>
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<td>436</td>
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<td>459</td>
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Figure 3.6, Percentage of vehicles in each measured average speed bin by method with absolute relative error in length for NGSIM I-80 (a) $\leq 1\%$, (b) $\leq 5\%$ at location 800 ft.

The length measurement results are encouraging, but it is important to also consider...
the specific application: length-based vehicle classification. As noted in [4], "the [length based] classification scheme is tolerant to large length estimation errors provided the true length is far from the boundary between two classes." In fact [4] found a classification error rate of 1.6% during free flow at a good dual-loop detector station and showed that most of the classification errors arose due to small length measurement errors for vehicles with lengths close to the boundary between two classes. Using the three length classes from [4], with boundaries at 28 ft and 46 ft, Table 3.3 shows the classification results for the NGSIM I-80 data from NM, CM+ and for reference, CM. NM had a classification error rate of 11/5,675 = 0.19%, CM+ had an error rate of 10/5,675 = 0.18%, and CM had an error rate of 16/5,675 = 0.28%.

<table>
<thead>
<tr>
<th>Length Class</th>
<th>Error Rate</th>
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<tbody>
<tr>
<td>NM</td>
<td>0.19%</td>
</tr>
<tr>
<td>CM+</td>
<td>0.18%</td>
</tr>
<tr>
<td>CM</td>
<td>0.28%</td>
</tr>
</tbody>
</table>
Table 3.3, Comparison of three methods: NM, CM+ and CM for vehicle classification accuracy verification using the NGSIM I-80 at location 800 ft. Where, 1, 2, 3 denote the vehicle length class: Class 1: Le ≤ 28 ft, Class 2: 28 ft < Le ≤ 46 ft, Class 3: Le > 46 ft.

<table>
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<th>True</th>
<th>Error Ratio</th>
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<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Measured</td>
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<td></td>
<td>3</td>
</tr>
<tr>
<td>Error Ratio</td>
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<table>
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<tr>
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<td></td>
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<tr>
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<tr>
<td>Error Ratio</td>
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</table>

<table>
<thead>
<tr>
<th>CM</th>
<th>True</th>
<th>Error Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Measured</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Error Ratio</td>
<td></td>
<td>0.13%</td>
</tr>
</tbody>
</table>

All of this analysis was repeated on US-101 with similar results, e.g., Table 3.4 and Figure 3.7a-b. Table 3.5 shows the classification performance on US-101. In this case NM had a classification error rate of 14/6,098 = 0.23%, CM+ had an error rate of 13/6,098 = 0.21%, and CM had an error rate of 19/6,098 = 0.31%.
Table 3.4. Number of vehicles in each measured average speed bin by method and across the entire NGSIM US-101 population with absolute relative error in length ≤1%, ≤5%, and correctly classified at location 1000 ft.

<table>
<thead>
<tr>
<th>V(mph)</th>
<th>#Vehicle</th>
<th>0-5</th>
<th>5-10</th>
<th>10-15</th>
<th>15-20</th>
<th>20-25</th>
<th>25-30</th>
<th>30-40</th>
<th>40-50</th>
<th>&gt;50</th>
<th>sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td></td>
<td>47</td>
<td>195</td>
<td>382</td>
<td>888</td>
<td>1586</td>
<td>1422</td>
<td>1405</td>
<td>160</td>
<td>13</td>
<td>6098</td>
</tr>
<tr>
<td>CM</td>
<td></td>
<td>17</td>
<td>103</td>
<td>306</td>
<td>788</td>
<td>1437</td>
<td>1291</td>
<td>1315</td>
<td>152</td>
<td>12</td>
<td>5421</td>
</tr>
<tr>
<td>CM-</td>
<td></td>
<td>1</td>
<td>9</td>
<td>51</td>
<td>201</td>
<td>574</td>
<td>473</td>
<td>651</td>
<td>71</td>
<td>6</td>
<td>2037</td>
</tr>
<tr>
<td>CM+</td>
<td></td>
<td>22</td>
<td>142</td>
<td>344</td>
<td>859</td>
<td>1540</td>
<td>1397</td>
<td>1397</td>
<td>158</td>
<td>12</td>
<td>5871</td>
</tr>
<tr>
<td>CMO</td>
<td></td>
<td>6</td>
<td>75</td>
<td>277</td>
<td>761</td>
<td>1387</td>
<td>1275</td>
<td>1281</td>
<td>145</td>
<td>13</td>
<td>5220</td>
</tr>
<tr>
<td>CMX</td>
<td></td>
<td>19</td>
<td>131</td>
<td>332</td>
<td>834</td>
<td>1497</td>
<td>1358</td>
<td>1356</td>
<td>154</td>
<td>12</td>
<td>5693</td>
</tr>
<tr>
<td>CMY</td>
<td></td>
<td>12</td>
<td>81</td>
<td>302</td>
<td>806</td>
<td>1476</td>
<td>1346</td>
<td>1352</td>
<td>153</td>
<td>12</td>
<td>5540</td>
</tr>
<tr>
<td>NM</td>
<td></td>
<td>25</td>
<td>149</td>
<td>341</td>
<td>858</td>
<td>1538</td>
<td>1396</td>
<td>1397</td>
<td>158</td>
<td>13</td>
<td>5875</td>
</tr>
</tbody>
</table>

| Absolute Relative Error in Length < 1% |
| CM     | 32  | 172 | 357 | 841 | 1501 | 1347 | 1333 | 152 | 13 | 5748 |
| CM-    | 3   | 29  | 138 | 535 | 1192 | 1142 | 1285 | 151 | 12 | 4487 |
| CM+    | 40  | 188 | 379 | 886 | 1584 | 1420 | 1405 | 160 | 13 | 6075 |
| CMO    | 14  | 143 | 344 | 815 | 1456 | 1305 | 1290 | 148 | 13 | 5528 |
| CMX    | 36  | 179 | 367 | 860 | 1536 | 1377 | 1362 | 156 | 13 | 5886 |
| CMY    | 17  | 151 | 360 | 857 | 1533 | 1375 | 1360 | 156 | 13 | 5822 |
| NM     | 40  | 191 | 379 | 885 | 1584 | 1420 | 1404 | 160 | 13 | 6076 |

| Correct Classification |
| CM     | 44  | 193 | 380 | 887 | 1579 | 1421 | 1402 | 160 | 13 | 6079 |
| CM+    | 46  | 194 | 382 | 888 | 1579 | 1421 | 1402 | 160 | 13 | 6085 |
| NM     | 45  | 194 | 382 | 888 | 1579 | 1421 | 1402 | 160 | 13 | 6084 |
Figure 3.7, Percentage of vehicles in each measured average speed bin by method with absolute relative error in length for NGSIM US-101 (a) ≤1%, (b) ≤5% at location 1000 ft.
The classification error rates observed herein during congestion are almost a full order of magnitude better than the empirical results from [4], that were collected under free flow conditions. This difference likely reflects several factors. First, [4] used sampled data at 240 Hz while the interpolated NGSIM data are continuous time. The discretized empirical data will exhibit errors due to the sampling and the subsample impacts are more pronounced at higher speeds. Second, over 70% of the observed accelerations had a magnitude below 2 mph/s, falling between the first two rows of Figures 3.2, 3.4, and 3.5. Third, although the NGSIM data include stopped vehicles that should exhibit large errors, their numbers are relatively small compared to the total flow.
The simple fact that flow goes to zero as speed drops means that relatively few stopping vehicles are actually observed in the data. A total of $110/5,675 = 1.94\%$ of I-80 vehicles stopped over the dual-loop detectors, while only $10/6,098 = 0.16\%$ of US-101 vehicles stopped over the dual-loop detectors. In fact for all speed bin below 30 mph the non-constant acceleration model proved to be the dominant vehicle-motion in the NGSIM data, while constant acceleration model dominated for 30-50 mph (see Appendix C). Finally fourth, the synthetic data do not have any detector errors. Even a healthy detector is likely to have the occasional measurement error of a few sampling cycles when recording the transition-times.

3.2.2 BHL validation

It is uncommon that individual vehicle actuations are recorded and it is even more uncommon to have ground truth vehicle length measurements. The previous section used empirical speeds and accelerations, but synthetic detector data. This section uses real detector data. The NGSIM I-80 dataset was collected in the Berkeley Highway Lab (BHL) [13], and BHL dual-loop detector Station 8 was within the NGSIM field of view. Station 8 had problems on the day of collection: it was off-line most of the time that the NGSIM data were collected and approximately 1% of the loop detector actuations were non-vehicle actuations due to splashover (the non-vehicle pulses were manually identified and excluded). There were still about 12 minutes of concurrent data that had actual loop detector measurements with independent ground truth vehicle lengths from NGSIM.
Initially the exact location of the detector station relative to the NGSIM coordinate system was unknown beyond the fact that the detectors were upstream of the Powell St. on-ramp located at 420 ft. Likewise, the time offset between the two databases was unknown. So we relied upon a brute force, exhaustive search to find the best combination of spatial and temporal offsets. First we synthesized dual-loop detector data in every lane from the NGSIM trajectories (as per the method in the previous section). This extraction was repeated at many locations along the NGSIM coordinate system, stepping the location of the synthetic dual-loop detectors by one foot increments between each successive trial. Using a window of ±3min, each of these synthetic detector stations was then compared to the actual dual-loop detector data to find the temporal offset yielding the best correlation between the two data streams, independently in each lane. Then, the location with the best overall correlation, 221 ft, was selected as the location of the actual detector station.

The process of matching the loop data to NGSIM was complicated by the fact that NGSIM sometimes does a poor job tracking the vehicles, e.g., during stop waves it was often the case that one of the NGSIM trajectories would overrun the trajectory of the vehicle ahead of it, erroneously indicating that two vehicles occupied the same point in time and space. Meanwhile, the loop detectors also appear to exhibit splashover problems and all non-vehicle pulses due to splashover were excluded. So after correlating the spatial and temporal offsets between the two concurrent data sets, a second pass was made through to manually match the synthetic pulses to the real detector pulses.

A total of 1,080 vehicles were seen in both data sets. To establish the size of the
loop detection zone we took the difference between the measured effective vehicle length from the loops and the corresponding NGSIM reported physical length for the given vehicle and calculated the average bias, which corresponded to a 7 ft detection zone.\textsuperscript{1} The true effective vehicle length was then set to the NGSIM reported physical length plus the 7 ft detection zone.

The left hand column of Figure 3.8 shows the scatter plot of measured effective length from the dual-loop detectors versus the corresponding NGSIM reported physical length plus a 7 ft detection zone, with one subplot for each of the three methods: NM, CM+, and CM. The horizontal and vertical lines in the plots show the divisions between length classes from [4] at 28 ft and 46 ft. The average absolute length error from each of the three methods is 2.5 ft (Average absolute length error by NM = 2.45 ft, average absolute length error by CM+ = 2.45 ft, and average absolute length error by CM = 2.48 ft) as shown in Figure 3.9.

\footnote{In general one does not normally know the size of the detection zone. With the BHL data we have the benefit of ground truth length data from NGSIM to minimize the average measurement error, thereby facilitating direct comparisons between the ground truth and measured lengths for the evaluation. The fact that the detection zone is larger than the physical loops is consistent with the fact that this station also exhibits splashover errors, both factors indicate that the detector sensitivity is set too high.}
Figure 3.8. Measured effective length versus true effective vehicle length from (a) NM on the BHL loop detector data, (b) CM+ on the BHL loop detector data, (c) CM on the BHL loop detector data, (d) NM on the NGSIM synthetic detector data, (e) CM+ on the NGSIM synthetic detector data, and (f) CM on the NGSIM synthetic detector data. All six subplots use the same exact set of passing vehicles.
Figure 3.9, (a) CDF of Length Error using BHL data, (b) CDF of Absolute Length Error using BHL data.

As was done with the NGSIM data, the arithmetic average, $\bar{v}$, of $V_r$ and $V_f$ is used to sort the results into bins by 5 mph from 0 to 30 mph and by 10 mph when higher than 30 mph. Table 3.6 shows the total number of vehicles falling into each speed bin and then for each of the three representative methods, reports the number of those vehicles that had an absolute relative length measurement error below 1% and below 5% respectively. Both CM+ and NM performed better than CM within 1% absolute relative error, and CM+ and NM are a little better than CM within 5% absolute relative error. The bottom of the table shows the vehicle classification in each speed bin. The three methods all perform quite well, and classify over 99% vehicles accurately. Although the performance is very close, both CM+ and NM correctly classified one more vehicle than CM.
Table 3.7 shows the performance of NM, CM+ and CM using the actual BHL loop detector data. The results are very good considering the average speed was 21 mph across these vehicles (median speed was 19 mph). Consistent with the NGSIM validation above, CM did as well as the other two methods, which suggests the acceleration impacts were very small (the average absolute acceleration for these vehicles was 2 mphps).
Table 3.7, Comparison of three methods: NM, CM+ and CM for vehicle classification accuracy verification using BHL data (left) and for the exact same vehicles the NGSIM synthetic data from NGSIM (right).

<table>
<thead>
<tr>
<th>NM</th>
<th>Actual BHL Data</th>
<th>Synthetic NGSIM Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>True Error Ratio</td>
<td>True Error Ratio</td>
</tr>
<tr>
<td>Measured</td>
<td>1</td>
<td>1025 2 3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2 18 0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0 1 31</td>
</tr>
<tr>
<td>Error Ratio</td>
<td>0.2% 18.2% 0.0%</td>
<td>1074</td>
</tr>
<tr>
<td>CM+</td>
<td>True Error Ratio</td>
<td>True Error Ratio</td>
</tr>
<tr>
<td>Measured</td>
<td>1</td>
<td>1025 3 0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2 18 0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0 1 31</td>
</tr>
<tr>
<td>Error Ratio</td>
<td>0.2% 18.2% 0.0%</td>
<td>1074</td>
</tr>
<tr>
<td>CM</td>
<td>True Error Ratio</td>
<td>True Error Ratio</td>
</tr>
<tr>
<td>Measured</td>
<td>1</td>
<td>1024 3 0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2 18 0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1 1 31</td>
</tr>
<tr>
<td>Error Ratio</td>
<td>0.3% 18.2% 0.0%</td>
<td>1073</td>
</tr>
</tbody>
</table>

For reference, the right hand side of Table 3.7 and Figure 3.8 show the results for the same vehicles, except now the loop detector data were synthesized strictly from the NGSIM trajectories in the same manner as Table 3.3 and 3.5. There are 3-4 fewer errors in the synthetic data, presumably reflecting the impacts of using real loop detectors. The synthetic data error rate is 0.3%, and is similar to the NGSIM analysis presented above.
3.3 Practical Considerations

In practice performance could be worse than the synthetic results presented in the NGSIM section due to sampling issues and detector errors. Typically detectors are sampled anywhere from 60 Hz to more than 1 kHz, e.g., the detectors in the BHL section are sampled at 60 Hz. At lower sampling frequencies short interval-time measurements will be very noisy due to the measurement granularity. For example a dual-detector sampling at 60 Hz with S=20 ft might only be able to resolve speeds to 5 mph in free flow traffic since the traversal time is so short. These sampling issues diminish greatly at lower speeds since the traversal and dwell-times become much longer.

To avoid having to address the impacts of detector errors, this thesis has been very specific about the need to use well-tuned detectors. Dual-detectors are prone to errors including pulse-breakup, splashover, sensitivity, etc. [14-18]. These errors will degrade performance and the resulting length measurement errors would be much larger at any speed for all seven of the methodologies discussed herein. For example, the size of the loop detector zone typically is unknown. Although the physical loops in the BHL are 6 ft across, the 7 ft detection zone size used above for BHL station 8 was chosen so that the average measured length error equals to 0. Given the true 7 ft detection zone, had we guessed a 6 ft zone, analytically we would expect length measurement errors in excess of 14% regardless of the length measurement method used. In this case we were able to find the size of the detection zone via the NGSIM vehicle measurements, in practice, one would need some other means of measuring the vehicle's physical length or the detection zone, e.g., [19].
Admittedly, this thesis is light on details of how to achieve well-tuned detectors. In general it is important for an operating agency to follow an established protocol for calibration and to quantify the reliability of the classification system. While discussing any specific calibration protocol is beyond the scope of this thesis, it is equally important to have an ongoing performance monitoring to ensure the detectors remain well-tuned, e.g., via [14-17]. If a detector fails these tests then the corresponding data are of questionable quality and the detector is in need of re-tuning.
CHAPTER 4

IMPROVED VEHICLE CLASSIFICATION IN CONGESTED TRAFFIC

Chapters 2-3 sought to improve the length measurement accuracy at dual-loop detectors. Even with the best algorithms, it is impossible to eliminate the impacts of unobserved acceleration on the length measurements from dual-loop detectors. So in this chapter we evaluate the feasible range of true vehicle lengths that could underlie a given combination of measured length, measured speed, and unobserved acceleration at a dual-loop detector. From this analysis we find that there are small uncertainty zones between length classes where the particular vehicle class is ambiguous. These uncertainty zones remain small down to about 10 mph and then grow exponentially down to about 5 mph. By mapping these uncertainty zones, most vehicles can be accurately sorted to a single length-class, while a few vehicles that fall within the zones are assigned to two or more classes. Using empirical data from stop-and-go traffic we find that this new approach assigns over 98% of the vehicles to a single class and reduces the classification error rate
by at least a factor of five.

This chapter strictly uses CM+, since Chapter 3 found it to be the most robust variant of the conventional methods during stop-and-go traffic conditions (the analysis is also repeated for NM in Appendix D). Using the vehicle motion models from Section 3.1 and synthetic dual-loop detector data, CM+ is applied to evaluate the impacts of constant speed, constant acceleration, non-constant acceleration, and coming to a complete stop on the measurement. Each of these four movement models is first considered individually, and then we combine the results. In each case we choose a vehicle's true length, initial speed, and acceleration profile; synthesize the detector actuations shown in Figure 2.1; calculate the average measured speed from Equation 21 and effective length from Equation 3 above; and compare the measurement to the true length.

\[ \bar{V} = \frac{V_r + V_f}{2} = \left( \frac{S}{TT_r} + \frac{S}{TT_f} \right)/2 \]  

(21)

4.1 Vehicle Classification Plane Generation

We present the results in the measured-length versus measured-speed plane to put them in the context of metrics that can be measured directly at conventional dual-loop detectors. In this work, for illustration purposes we adopt the classification length bins commonly used by the Ohio Department of Transportation (ODOT), as discussed in [4], and repeated below. In most cases it is sufficient to evaluate the boundary values between vehicle classes, i.e., 28 ft and 46 ft used by ODOT.
Class 1: 0 feet < effective vehicle length ≤ 28 feet
Class 2: 28 feet < effective vehicle length ≤ 46 feet
Class 3: effective vehicle length > 46 feet

4.1.1 Establishing the Range of Acceleration

To establish the range of reasonable acceleration for this work, we employ the NGSIM I-80 dataset from Section 3.2 once more. Figure 4.1 shows the probability mass function of the accelerations recorded for all vehicles, at all locations in the NGSIM dataset. Over 70% of the accelerations range from -2 mphps to 2 mphps, and over 50% range from -1 to +1 mphps, so in the following sections we use $a = \pm 1$ mphps or $a = \pm 2$ mphps as our reference values.

![Figure 4.1, Acceleration distribution of all vehicles of NGSIM I-80 data.](image)
4.1.2 Measured Class Boundaries Given a Constant Speed

The simplest vehicle motion is the constant speed model, whereby the vehicle passes a dual-loop detector with a constant speed. In this case, there is no acceleration and the vehicle does not stop while traversing the detector, thus $V_r = V_f$ and $T_u = T_d$. So the measured length from Equation 3 should equal the true effective vehicle length for the given vehicle. Therefore, under constant speed the boundaries between measured length classes are equal to the boundaries between the true length classes for all measured speeds. The bold lines in Figure 4.2a show the boundaries between the measured vehicle length classes.
Figure 4.2, (a) Vehicle Classification for Constant Speed Model, (b) Vehicle Classification for Constant Acceleration Model, (c) Vehicle Classification for Non-Constant Acceleration Model, and (d) Vehicle Classification for Stop Model.

4.1.3 Measured Class Boundaries Given a Non-Stop Constant Acceleration

The simplest vehicle motion that includes acceleration is one of constant
acceleration, with no stops over the dual-loop detector. For the boundary between class 1 and 2 we set the true effect of vehicle length, $L_e$, to be 28 ft, and for the boundary between class 2 and 3 we set $L_e$ to be 46 ft. Setting the loop spacing, $S$, to be 20 ft, we vary the true initial speed, $V_0$, from 0 to 100 mph, at $\Delta V = 0.1$ mph increments, and set acceleration, $a$, to $+2$ mphs and $-2$ mphs. Synthesizing the detector actuations from Figure 2.1, then calculating the average measured speed from Equation 21 and measured effective length from Equation 3, the bold curves in Figure 4.2b show how the boundary curves between the true vehicle length classes are pulled to shorter vehicle lengths as speeds approach the stop region in the presence of a constant acceleration. These curves are truncated when they hit the dashed curve, denoting the threshold where the given vehicle would come to (or start from) a stop at the given acceleration. Note that the average measured speed differs from $V_0$, and in this case positive and negative accelerations both lead to very similar boundary curves. Within the non-stop region the resulting error in the boundary curve from the measured length is small down to 10 mph and then starts to grow as the average speed drops, until reaching the edge of the stop region. The general shape of the boundaries between classes and the threshold of the stop region remain the same at different values of $|a|$, but as $|a|$ shrinks, the associated speeds also drop, and the curves compress to the left.

### 4.1.4 Measured Class Boundaries Given a Non-constant Acceleration

To capture the non-constant acceleration case we use a piecewise linear acceleration profile as shown in Figure 3.3a for the given vehicle passing over the dual-loop detector.
This model is characterized by the accelerations, \( a_i \) and \( a_j \); initial speed, \( V_0 \); and the speed at the inflection point, \( V_x \); while the two time periods, \( t_i \) and \( t_j \) denote the time spent by the vehicle during the given acceleration and can be expressed as a function of the other variables. For illustrative purposes we consider the four following combinations:

- scenario 1, \( a_i = 1 \text{ mphps} \), and \( a_j = 2 \text{ mphps} \);
- scenario 2, \( a_i = 2 \text{ mphps} \), and \( a_j = -2 \text{ mphps} \);
- scenario 3, \( a_i = -2 \text{ mphps} \), and \( a_j = 2 \text{ mphps} \); and
- scenario 4, \( a_i = -1 \text{ mphps} \), and \( a_j = -2 \text{ mphps} \).

In this model we set \( V_x \) denoting the speed at which the vehicle will change acceleration, set \( t_i = t_j \), and vary \( V_x \) from 0 to 100 mph, at \( \Delta V = 0.1 \text{ mph increments} \) (excluding all combinations that would yield a negative \( V_0 \) or final speed at time \( t_f \) in Figure 3.3a). Hence for each case the initial speed \( V_0 \) is calculated from \( a_i, a_j, L_c, S \) and \( V_x \), and once more we synthesize the detector actuations. Figure 4.2c shows the range of outcomes from the two boundary curves, mapping out an uncertainty zone between the distinctly discernable length classes. For both uncertainty zones the top right of the zone comes primarily from scenario 2, the lower edge of the zone arises primarily from scenarios 1 and 4, and the left edge of the uncertainty zone from scenario 3, corresponding to the edge of the stop region when \( V_x = 0 \). So in this case, at 20 mph the lower uncertainty zone exhibits a range of 1.2 ft and the upper uncertainty zone exhibits a range of 1.9 ft. At 15 mph these zones grow to 2.0 ft and 3.8 ft, respectively. The top of

\[^2\text{Because this plot uses four different combinations of accelerations, the stop region boundary is no longer a well-defined curve, as it was in Figure 4.2b.}\]
the uncertainty zones quickly exceeds the maximum feasible vehicle length as speeds drop further, and in the case of the lower zone actually bends back towards higher measured speeds at longer measured vehicle lengths.

4.1.5 Measured Class Boundaries Given a Stop Over the Dual-Loop Detector

So far we have considered acceleration in the absence of stops, but in stop-and-go traffic, vehicles will stop over the dual-loop detector. Because $L_e > S$ for both boundary curves, when one of these vehicles stop it will do so over one or both of the loop detectors. First, consider the case where the vehicle stops over the upstream detector, before reaching the downstream detector. In the context of Figure 2.1, $t_1$ will move to the left by the duration of the stop time, impacting both $TT_r$ and $T_u$. In this case the length measurement error will be relatively small because these extensions from the stop time partially cancel each other out in Equation 3. On the other hand if the vehicle stops over both detectors, both $t_1$ and $t_3$ will move to the left by the duration of the stop time (note that the figure illustrates the case with $L_e < S$, whenever $L_e > S$ $t_2$ and $t_3$ will swap their temporal order). So now both dwell times will be extended by the stop time, but neither traversal time will include the stop time. This imbalance will lead to a large error in Equation 3 and the measured vehicle length will be much longer than the true vehicle length.

Extending the non-constant acceleration model to include a stop time, we use the piecewise linear acceleration profile shown in Figure 3.3b for a vehicle stopping over the dual-loop detector at the worst possible location relative to the loops- i.e., with the
vehicle stopped over both loops and centered relative to the two loops. The only things that we change from the last section is the addition of the stop time, $\Delta t$, we only consider the stop region ($V_x=0$), and now we only use scenario 3 because it traces out the lower bound of the uncertainty zones. The bold curves in Figure 4.2d show the case when $\Delta t = 0$, which means the vehicle comes to a complete stop over the detection zone and then immediately accelerates away. For speeds just below the right hand edge of the stop region we see the boundary drops to the lowest measured vehicle length and then quickly shoots up beyond the largest feasible vehicle (while also moving to higher average measured vehicle speed). Keep in mind that this is the lower bound of the class above for the given acceleration profile, with the upper bound already being established in Figure 4.2c. For longer $\Delta t$ the two boundaries in Figure 3d shift to lower speeds and lengths.

After including non-zero stop times and vehicles that come to a stop over just one loop, most measurements falling in the stop region with measured length between 26 ft and 42 ft could come either from a class 1 or class 2 vehicle, while a measured length above 42 ft could come from a vehicle in any one of the three classes.

### 4.1.6 Class Boundaries without Knowledge of the Acceleration

Figure 4.3b shows the intersection of all of the boundaries from Figure 4.2, with $|a| = 2$ mphs. Figure 4.3a repeats this analysis except now $|a| = 1$ mphs and Figure 5c repeats in analysis with $|a| = 4$ mphs. The three plots exhibit a similar shape; however, as the magnitude of acceleration increases, the curves shift to the right and the
inclination increases, reflecting the impacts of acceleration on the vehicle length measurement accuracy. Figures 4.2 and 4.3b arise from the same specific choice of the acceleration profile. In general the acceleration profile cannot be measured from a dual-loop detector and each vehicle likely chooses its own profile without regard to the average conditions used thus far in our analysis. Capturing the resulting measured lengths and speeds from all feasible accelerations, Figure 4.4 steps through acceleration magnitudes from 0 to 4 mphps and records all of the possible true vehicle classes observed at the given point on measured length and speed plane. The three shaded regions: ABHG, BCDH and GHEF, bound the length and speed measurement pairs that could arise from vehicles of multiple classes, namely: classes 1&2&3, 2&3, and 1&2, respectively. The remainder of the plane is un-shaded, denoting that in the absence of detector errors those measured length and speed pairs could only arise from a single true vehicle class.

---

3 This figure includes constant acceleration with $|a| \leq 4$ mphps, as well as non-constant acceleration and stopped vehicles with $|a_i| + |a_j| \leq 4$ mphps.
Figure 4.3, Theoretical vehicle classification plane by CM+ with acceleration equal to (a) $\pm 1$ mphs, (b) $\pm 2$ mphs, (c) $\pm 4$ mphs.
Figure 4.4, The length-based vehicle classification plane by CM+ showing the uncertainty zones where errors in the measured length could lead to a misclassification; the numbers on this plot denote the vehicle class/classes that fall within the given area.
4.2 Vehicle Classification Performance Evaluation Using Empirical Data

To evaluate this length-based classification scheme we use two empirical data sources. The first is the I-80 NGSIM data set, and the second empirical data set consists of actual detector actuations from the Berkeley Highway Laboratory (BHL) dual-loop detector station 8 that falls within the NGSIM surveillance region. Both of these data sets were discussed in detail in Section 3.2.

4.2.1 NGSIM synthesis and validation

This section uses the NGSIM I-80 dataset to evaluate the classification scheme. We simulated a dual-loop detector in each lane, with the leading edge of the upstream loop detector located at 1,000 ft along the road in the NGSIM coordinate system and used the same process described in Section 3.2.1 for synthesizing the detector data.

Figure 4.5a shows a scatterplot of the measured versus the true effective of vehicle length. The solid horizontal and vertical lines in the plot show the boundaries between adjacent vehicle classes relative to the true effective vehicle length. Different symbols are used to denote whether the given vehicle was correctly classified into a single class (points) or multiple classes (circles); or was incorrectly classified (cross). Figure 4.5b shows the cumulative distribution function (CDF) of the average measured speed at this detector location. With a median speed of 17 mph and 80% of the speeds below 25 mph, there was considerable congestion, but as can be seen in Figure 4.5a, most of the vehicles are already correctly classified using the conventional constant speed boundaries, without
making any accommodation for acceleration.

Figure 4.5, (a) Scatter plot by CM+ comparing the measured versus true NGSIM length-based vehicle classification at the study location, (b) CDF of average measured speeds for the same vehicles by NGSIM I-80 at 1000 ft.

Figure 4.6a plots the measured effective vehicle length (Equation 3) versus the measured speed (Equation 21) for each of these vehicles, sorted by the true vehicle class as denoted with the given marker symbol. Consistent with Figure 4.5, most of these vehicles are already correctly classified using the constant speed boundaries shown with dashed horizontal lines. Superimposed on top of this plot are the uncertainty zones from Figure 4.4. Most of the vehicles falling in these uncertainty zones were already correctly classified using the constant speed boundaries; however, most of the vehicles that would
have been misclassified using the constant speed boundaries also fall within these uncertainty zones. Figure 4.6b shows the misclassifications that remain after excluding all of the vehicles that were correctly classified either into a single class or to an uncertainty zone that included the correct class. Table 4.1 quantifies these results. The right-hand side shows the results using the conventional, constant speed boundaries, and only 7 vehicles are misclassified. These results are probably a little better than one would expect to see at a real detector station since the measurement process excluded the possibility of detector errors from occurring. In any event, the left-hand side of the table shows the results after accounting for the uncertainty zones. A total of 58 vehicles (just over 1%) are assigned to two or more classes. The number of misclassified vehicles dropped to just 1 (improved by a factor of 7) when using the uncertainty zones.
Figure 4.6, (a) Vehicle classification by CM+ using measured effective vehicle length versus measured speed for all of the NGSIM data, (b) repeating part a, but only showing the misclassifications that do fall outside of the correct region or uncertainty zones by NGSIM I-80 at 1000 ft.

Table 4.1, The left-hand side of this table shows a comparison of the measured length-based vehicle class by CM+ when including the uncertainty zones against the true length-based vehicle class. The right-hand side of this table repeats a comparison using only the constant speed boundaries between classes by NGSIM I-80 data at location 1000 ft.
4.2.2 BHL validation

Using the loop detector data from Section 3.2.2, Figure 4.7 repeats the comparisons from Figure 4.5, only now applied to the actual loop detector data from BHL station 8. Comparing the two figures, on average the speeds were higher at BHL station 8, in part because it was towards the upstream end of the NGSIM segment and in part because it comes strictly from the first 15 minute period of the NGSIM I-80 data set, which was the least congested of the three NGSIM time periods.

![Figure 4.7](a) Scatter plot by CM+ comparing the measured versus true NGSIM length-based vehicle classification for BHL data of station 8, (b) CDF of average measured speeds for the same vehicles.

Figure 4.8a plots the measured effective vehicle length versus the measured vehicle
speed for each of these vehicles, sorted by true vehicle class as denoted with the given marker symbol. Superimposed on top of this plot are the uncertainty zones from Figure 4.4. Figure 4.8b shows the one misclassification that remains after excluding all of the vehicles that were correctly classified either into a single class or to an uncertainty zone that included the correct class. Table 4.2 quantifies these results. The right-hand side shows the results using the conventional, constant speed boundaries, and six vehicles are misclassified. The left-hand side of the table shows the number of misclassified vehicles when using the uncertainty zones and the error rate dropped to just 1 (improved by a factor of 6 over the constant speed boundaries). A total of 14 vehicles (1.3%) are assigned to two or more classes in this case.

Figure 4.8, (a) Vehicle classification by CM+ using measured effective vehicle length versus measured speed for BHL data of station 8, (b) misclassifications using measured effective vehicle length versus measured speed.
Table 4.2. Using the real detector actuations from the BHL station, the left-hand side of this table shows a comparison of the measured length-based vehicle class when including the uncertainty zones against the true length-based vehicle class. The right-hand side of this table repeats a comparison using only the constant speed boundaries between classes.

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<th>using the conventional constant speed boundaries</th>
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<tr>
<td>Percent</td>
<td>94.6%</td>
<td>1.4%</td>
</tr>
</tbody>
</table>

4.2.3 Discussion

Contrary to conventional wisdom we found that the conventional, constant speed boundaries performed surprisingly well down to 15 mph for both of the empirical evaluation data sets. As seen in Figure 4.1, almost 60% of the accelerations are within -1 mphps to 1 mphps; thus, the range of accelerations tended to be much closer to zero then was modeled in Figure 4.4. So for vehicles that did not come to a stop over the detectors, the constant speed boundaries were already a pretty good match, as shown in Figure 4.3a with the magnitude of acceleration limited to 1 mphps. Most of the classification errors that did occur using the constant speed boundaries fell within the uncertainty zones predicted by this work, as shown in in Tables 4.1 and 4.2.

Comparing the performance from purely synthetic data derived from the NGSIM dataset against the performance from the real loop detector actuations in the BHL data we
find that the error rate was higher in the BHL data even though speeds were also higher. We attribute this outcome to the fact that the synthetic data precludes the possibility of a detector error while the real data includes detector errors.

This method is meant to extend meaningful length-based vehicle classification to sites that see some congestion. Reviewing the different subplots in Figures 4.2-4.5, clearly the stop case and even some of the low speed, non-constant acceleration cases can yield very large errors in the measured lengths. Fortunately, very few vehicles actually pass the dual-loop detector at these low speeds, since the lower the speed the lower the flow and the lower the flow the fewer vehicles are seen passing a dual-loop detector.
CHAPTER 5

CONCLUSIONS

This thesis examined length measurement for vehicle classification at dual-detectors on a freeway during congested conditions where speed is low enough that acceleration cannot be neglected. First, we considered six variations of the conventional length measurement method (CM\textbullet), all of which assume acceleration is zero. In response to the shortcomings, we developed a new method for measuring length (NM) that instead assumes acceleration is constant, but might be non-zero. We then evaluated all seven of the length measurement methods under different vehicle-motions (first using strictly defined motions, then empirically observed trajectories, and finally using actual loop detector data).

The six CM variants exhibited markedly different performance under the strictly defined motions, with CM+ showing the best results among the six conventional methods. Meanwhile, NM was slightly better than CM+ across all seven methods, but, only by the smallest of margins. All of the methods worked well given zero acceleration. Under constant acceleration, consider Figure 3.2a and b when \(L_e = 50 \text{ ft}\) and \(a = \pm 3 \text{ mphs}\), the absolute relative error from CM exceeds 5\% for \(V_0 < 25 \text{ mph}\), illustrating why
operating agencies are reluctant to use conventional methods in congestion. Recall that across all seven methods, the absolute error increases with $L_e$ and the reciprocal of $V_0$. In contrast, the error from CM+ remains below 5% under more challenging conditions: down to $V_0 = 6$ mph with $L_e = 70$ ft, suggesting that length measurements and classification could be extended to these lower speeds provided that care is taken to ensure that the detectors are well tuned. Considering typical accelerations, $|a| \leq 3$ mph/s we see that NM, CM+, CMX and CMY in Figure 3.4 all have errors below 5% for speeds down to 20 mph for $L_e = 70$ ft and similar performance at lower speeds for shorter values of $L_e$.

In the empirical validation CM did almost as well as CM+ and NM in congestion, suggesting that the regular method is already doing quite well for the evaluation datasets. In other words, the extreme accelerations and the worst-case stop locations from the earlier motion analysis were fairly uncommon in the empirical data. The good performance is also due in part to the fact that, "the [length based] classification scheme is tolerant to large length estimation errors provided the true length is far from the boundary between two classes," [4]. Whether these results are typical of other locations will require further data collection. In any event, the empirical results also underscore the importance of using well-tuned detectors, otherwise the length measurement errors would be much larger at any speed for all seven of the methodologies discussed herein.

We suspect that it is possible to realize further gains by considering the differences between the various length measurement methods. For example, using an exhaustive search similar to the way we established the uncertainty zones, it may be possible to use
the differences between $L_{CM_r}$ and $L_{CM_f}$ (Equation 2) to establish that one or the other is distorted due to a vehicle stopping over just one of the loop detectors. In this case the CM length measurement from the loop detector with the stop and the CM+ length measurement will both be distorted while the CM length measurement from the other detector should typically be more accurate in this special case. Or in an even simpler case, one should have higher confidence in the vehicle classification when all seven methods yield the same vehicle class. Comparing the different length measurements will likely yield better performance than any one method taken alone; however, work on this idea is left to future research.

In any event, all seven of the length measurement methods will yield poor performance when a vehicle stops over the dual-loop detector. Recognizing the severity of the measurement error when slow moving vehicle accelerates or stops near the dual-loop detector, we evaluated the feasible range of true vehicle lengths from CM+ that could underlie a given combination of measured length, measured speed, and unobserved acceleration at a dual-loop detector. From this analysis we found that there are small uncertainty zones between length classes where the particular class is ambiguous given the measured vehicle speed and length. By mapping these uncertainty zones, most vehicles can be accurately sorted to a single length-class, while a few vehicles that fall within the zones are assigned to two or more classes. Using empirical data from stop-and-go traffic we found that this new approach assigns over 98% of the vehicles to a single class, and reduces the classification error rate by at least a factor of five relative to the conventional constant speed boundary method.
Contrary to conventional wisdom we found that the conventional, constant speed boundaries performed surprisingly well down to 15 mph for both empirical evaluation data sets. Most of the classification errors that did occur in the empirical data using the constant speed boundaries fell within the uncertainty zones predicted by this work. As such, the greatest benefits of this work come at the lowest speeds, i.e., below 15 mph.
REFERENCES


APPENDIX A

TRANSITION-TIME CALCULATION FOR NON-CONSTANT ACCELERATION MODEL

The following equations show the process of calculating the transition-times, \( t_1, t_2, t_3, t_4 \), for non-constant acceleration and stop models. The vehicle measurement equation is complicated for non-constant acceleration model and stop model. Based on the different locations of inflection point, at which the acceleration changes from the first value, \( a_i \), to the second value, \( a_j \), shown in figure 3.3, the expression can be sorted in to six different cases, as follows:

\[
t_i = \frac{V_x - V_0}{a_i}
\]

\[
t_j = -\frac{V_x + \sqrt{V_x^2 - 2a_j((V_x^2 - V_0^2)/2a_i - S - L_o)}}{a_j}
\]

\[
t = t_i + t_j
\]
When $L_e \leq S$

Case 1: $(V_o+V_x) \cdot t_2 / 2 < L_e$

$t_1 = 0$

$$t_2 = t_1 + \frac{-V_x + \sqrt{V_x^2 + 2a_j(L_e - (V_o + V_x) \cdot t_2 / 2)}}{a_j}$$

$$t_3 = t_1 + \frac{-V_x + \sqrt{V_x^2 + 2a_j(S - (V_o + V_x) \cdot t_2 / 2)}}{a_j}$$

$t_4 = t$

Case 2: $(V_o+V_x) \cdot t_i / 2 \geq L_e \& (V_o+V_x) \cdot t_i / 2 < S$

$t_1 = 0$

$$t_2 = \frac{-V_o + \sqrt{V_o^2 + 2a_i \cdot L_e}}{a_i}$$

$$t_3 = t_1 + \frac{-V_x + \sqrt{V_x^2 + 2a_j(L_e - (V_o + V_x) \cdot t_2 / 2)}}{a_j}$$

$t_4 = t$

Case 3: $(V_o+V_x) \cdot t_i / 2 \geq S \& (V_o+V_x) \cdot t_i / 2 \leq L_e + S$

$t_1 = 0$

$$t_2 = \frac{-V_o + \sqrt{V_o^2 + 2a_i \cdot L_e}}{a_i}$$

$$t_3 = \frac{-V_o + \sqrt{V_o^2 + 2a_i \cdot S}}{a_i}$$

$t_4 = t$
When $L_e \geq S$

Case 4: $(V_o + V_x) \cdot t_i / 2 >= 0 \& (V_o + V_x) \cdot t_i / 2 < S$

\[ t_1 = 0 \]

\[ t_2 = t_1 + \frac{-V_x + \sqrt{V_x^2 + 2a_j \cdot (t_i - (V_o + V_x) \cdot t_i / 2)}}{a_j} \]

\[ t_3 = t_1 + \frac{-V_x + \sqrt{V_x^2 + 2a_j \cdot (S - (V_o + V_x) \cdot t_i / 2)}}{a_j} \]

\[ t_4 = t \]

Case 5: $(V_o + V_x) \cdot t_i / 2 >= S \& (V_o + V_x) \cdot t_i / 2 < L_e$

\[ t_1 = 0 \]

\[ t_2 = t_1 + \frac{-V_o + \sqrt{V_o^2 + 2V_0 \cdot (L_e - (V_o + V_x) \cdot t_i / 2)}}{a_j} \]

\[ t_3 = \frac{-V_o + \sqrt{V_o^2 + 2a_i \cdot S}}{a_i} \]

\[ t_4 = t \]

Case 6: $(V_o + V_x) \cdot t_i / 2 >= L_e \& (V_o + V_x) \cdot t_i / 2 <= L_e + S$

\[ t_1 = 0 \]

\[ t_2 = \frac{-V_o + \sqrt{V_o^2 + 2a_i \cdot L_e}}{a_i} \]

\[ t_3 = \frac{-V_o + \sqrt{V_o^2 + 2a_i \cdot S}}{a_i} \]
t_4=t

Based on t_1, t_2, t_3 and t_4 four values:

TT_r = t_3 - t_1

TT_f = t_4 - t_2

T_u = t_2 - t_1

T_d = t_4 - t_3

V_r = \frac{s}{TT_r}

V_f = \frac{s}{TT_f}

Thus, plug the above variables into seven method formulas expressed at the beginning of chapter 2, measured effective vehicle length can be obtained as shown in constant acceleration model. Note that V_x is the instant speed for inflection point, if we apply a non-constant acceleration model, V_x > 0, otherwise, we apply a stop model with V_x = 0.
APPENDIX B

VEHICLE STOP LOCATION ANALYSIS

As shown in figure B.1 below, AB is the total distance traveled by a vehicle from the point where it enters the upstream loop detector to the point where it completely passes the downstream loop detector. When one vehicle stops over the dual-loop detector at different locations, the error ratio will vary related to the position of stop location. Figure B.2 gives an illustration corresponding to Figure 3.5a, and the horizontal axis is stop location denoting the distance from A to the front bumper of the vehicle that stops over the dual-loop detector. As we can see from Figure B.2, the peak error for the six methods except for CM- for shortest vehicle, and for the five methods except for CM- and CM for longer vehicles, always occurs around the middle of AB, denoting O in Figure B.1.
Figure B.1, Schematic of a vehicle passing over a dual-loop detector.

Figure B.2, Family diagram of absolute relative error in length, $Le$, versus stop location (e.g. distance $AO$), for the seven methods under the stop model with $a_i<0$, $a_j>0$ and $\Delta t = 0$ sec. $Le$ is constant in a given column of subplots, but increases from left to right, while $V_0$ is constant in a given row of subplots, increasing from top to bottom refer to figure 3.5a.
APPENDIX C

VEHICLE ACCELERATION DISTRIBUTION

Based on the NGSIM data, we could observe real acceleration was recorded every 0.1 second when each vehicle passes paired loop sensors, and the acceleration values vary even for a short period of each vehicle passing the sensors. The Tables 3.1 and 3.2 show the distribution for each vehicle motion related to average measured vehicle speed for the I-80 and US-101 data sets, where we consider the vehicle with acceleration in ±0.5 mph/s is constant speed model, the vehicle with acceleration difference within ±1 mph/s is constant acceleration model, the vehicle with one or more stops during passing over the dual-loop detectors is stop model, and the rest are classified into non-constant acceleration model.
Table C.1, Vehicle motions distribution in each measured speed bin by NGSIM I-80 data at location 800 ft.

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Table C.2, Vehicle motions distribution in each measured speed bin by NGSIM US-101 data at location 1000 ft.

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APPENDIX D

PROCESS OF VEHICLE CLASSIFICATION IN THE PRESENCE OF ACCELERATION BY NM

Figure D.1, (a) Vehicle Classification for Constant Speed Model by NM, (b) Vehicle Classification for Constant Acceleration Model by NM ($a = +2$ mphs), (c) Vehicle Classification for Non-Constant Acceleration Model by NM (4 different combinations of $a_i$ and $a_j$ shown), (d) Vehicle Classification for Stop Model by NM ($a_i = -2$ mphs, $a_j = +2$ mphs).
(Figure D.1 Continued)

(Figure D.2 Continued)

Figure D.2, Theoretical vehicle classification plane by NM with acceleration equal to (a) +/-1 mphps, (b) +/-2 mphps, (c) +/-4 mphps.
(Figure D.2 Continued)
Figure D.3, The length-based vehicle classification plane by NM showing the uncertainty zones where errors in the measured length could lead to a misclassification; the numbers on this plot denote the vehicle class/classes that fall within the given area.
Figure D.4, Scatter plot by NM comparing the measured versus true NGSIM length-based vehicle classification at the study location, (b) CDF of average measured speeds for the same vehicles by NGSIM I-80 data at location 1000 ft.
Figure D.5, Vehicle classification by NM using measured effective vehicle length versus measured speed by NGSIM I-80 data at location 1000 ft.

Figure D.6, (a) Scatter plot by NM comparing the measured versus true NGSIM length-based vehicle classification for BHL data of station 8, (b) CDF of average measured speeds for the same vehicles.
Figure D.7, (a) Vehicle classification by NM using measured effective vehicle length versus measured speed for BHL data of station 8, (b) repeating part a, but only showing the misclassifications that do fall outside of the correct region or uncertainty zones.
Table D.1, The left-hand side of this table shows a comparison of the measured length-based vehicle class by NM when including the uncertainty zones against the true length-based vehicle class. The right-hand side of this table repeats a comparison using only the constant speed boundaries between classes by NGSIM I-80 data at location 1000 ft.

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<td>Percent</td>
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Table D.2, Using the real detector actuations from the BHL loop detector station at 221 ft, the left-hand side of this table shows a comparison of the measured length-based vehicle class when including the uncertainty zones against the true length-based vehicle class. The right-hand side of this table repeats a comparison using only the conventional constant speed boundaries between classes.

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