

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**SPEED SURVEY: A CASE STUDY ON A BASIC FREEWAY SEGMENT OF
O-2, ISTANBUL**

M.Sc. THESIS

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Department of Civil Engineering

Transportation Engineering Programme

MAY 2015

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MAY 2015

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**HIZ ETÜDÜ: İSTANBUL O-2 OTOYOLUNUN TEMEL BİR KESİMİNİN
ÖRNEĞİ**

YÜKSEK LİSANS TEZİ

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To my family,

FOREWORD

I always was interested in transportation and traffic subjects in my hometown, Tabriz. Tabriz is not a developed city in these issues and also is a big city with growing population. This causes increasing of carownership and traffic congestion. These were the main reasons that I selected civil engineering in bachelor's degree. At that time, I took traffic and transportation engineering courses at University of Tabriz. These courses, researching of these issues and participating in solving traffic problems in my city in the future motivated me to continue my graduate school in Transportation Engineering. So, I decided to select a crowded metropolitan city like Istanbul with many traffic problems and good education level and researches in this field. Speed is one of the most important factors in road safety and road capacity. Therefore, I was motivated to do my thesis about speed.

I would like to thank my supervisor Assoc. Prof. Dr. Kemal Selçuk ÖĞÜT for his guidance throughout my period of thesis. I am grateful to Assoc. Prof. Dr. Kemal Selçuk ÖĞÜT for his technical and mental support from the beginning of my graduate school life.

As a foreigner student in Turkey, my dear friends; Shahin SHAKIBAEI and Esad ERGİN always supported me mentally and with their presence it became easier for me to manage the life in Istanbul.

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ABBREVIATIONS

ANOVA	: Analysis of Variance
CDF	: Cumulative Distribution Function
CW	: Continuous Wave
FFS	: Free Flow Speed
FHWA	: Federal Highway Administration
FMCW	: Frequency Modulated Continuous Wave
FSM	: Fatih Sultan Mehmet
GPS	: Global Positioning System
HCM	: Highway Capacity Manual
K-S	: Kolmogorov-Smirnov
K-W	: Kruskal-Wallis
LOS	: Level of Service
MSD	: Maximum Speed Difference
PDF	: Probability Density Function
PI&E	: Public Information and Education
RFR	: Road Flow Rate
RS	: Road Speed
RSL	: Rational Speed Limit
RTMS	: Remote Traffic Microwave Sensor
TRB	: Transportation Research Board
VDS	: Video Detection System
VMS	: Variable Message Sign
VSL	: Variable Speed Limit

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SPEED SURVEY: A CASE STUDY ON A BASIC FREEWAY SEGMENT OF O-2, ISTANBUL

SUMMARY

Speed is one of the fundamental variables of road traffic flow that stands as an important evaluation criterion for traffic analyses in several aspects. In particular, varieties of speed variable, such as average speed, free flow speed, optimum speed (capacity speed), acceleration/deceleration speed and so on, have been explicitly considered in the analysis of not only road safety but also road capacity. In the purpose of analyzing speeds and realizing speed differentiations on freeway traffic, this study presents a case study conducted on a basic freeway segment of O-2 in Istanbul.

Chapter one comprises a brief introduction to the study. The fundamentals of road traffic flow are explained in chapter two, briefly including traffic flow measures and variables of traffic flow. Then, the fundamental relationships of traffic flow variables are presented with graphs.

Chapter three of this thesis contains a brief literature review. Temporal and spatial variability of free speed along freeway, speed variation and freeway traffic congestion, and freeway speeds and speed variations preceding crashes are the main points of this chapter. The case study of this thesis is explained in chapter four. The numerical implementations for field observations speed data are the major points of chapter four. This chapter encompasses statistical evaluations for speed data of field observations.

The speed data are analyzed into two main areas such as uncongested and congested areas. In the context of this thesis, Kruskal-Wallis (K-W) tests were performed to evaluate the effects of changes in lanes, weeks, and days of week on the speeds at uncongested and congested flow areas separately.

In this study, Kolmogorov-Smirnov (K-S) tests were implemented to determine the distribution of lane and road speed data of free flow speed region. The analyzed distributions are normal, lognormal, gamma, gumbel, exponential and uniform distributions.

Furthermore, the regression analyses were carried out in order to investigate the relationship between maximum speed difference across lanes and road speed. These investigations were performed at uncongested and congested areas, separately. Moreover, the relationship between maximum speed difference across lanes and road flow rate were evaluated by applying regression analyses for both uncongested and congested areas separately.

In the final chapter, chapter five, the conclusions of this thesis are given. The results of K-W tests of speed data at uncongested flow area show that the speeds generally vary significantly across lanes; however, the variation of speeds across weeks and

days are not that much obvious. The results of K-W tests of speed data at congested flow area show that the speeds do not vary significantly from one lane to the others, from one specific day of week to the others, and from one day of week to the other at some analyzed locations.

Moreover, the conclusions of 35 K-S tests at road sections indicate that the free flow speed data fit to normal distribution 20 times, gamma distribution 19 times, lognormal distribution 18 times and gumbel distribution 3 times.

It is concluded from the results of regression analyses for uncongested and congested areas that there is moderate relationship between maximum speed difference across lanes and road speed in %50 cases. Additionally, the results of regression analyses for uncongested and congested areas indicate that there is moderate relationship between maximum speed difference across lanes and road flow rate in %30 cases. The maximum speed difference across lanes decreases as the road flow rate increases.

HIZ ETÜDÜ: İSTANBUL O-2 OTOYOLUNUN TEMEL BİR KESİMİNİN ÖRNEĞİ

ÖZET

Birçok açıdan trafik analizi için önemli bir değerlendirme kriteri olan hız, karayolu trafik akımının temel değişkenlerinden biridir. Özellikle, ortalama hız, serbest akım hızı, optimum hız (kapasite hızı), hızlanma/yavaşlama gibi hızın değişimleri yalnızca karayolu güvenliğinde değil, karayolu kapasite analizlerinde de açıkça dikkate alınmaktadır. Bu tez çalışması, otoyol trafiğinde hızları analiz etmek ve hız farklılıklarını anlamak amacıyla İstanbul O-2 otoyolunun bir kesiminde örnek bir çalışma içermektedir.

İstanbul sahip olduğu nüfus itibarıyla kalabalık ve belirgin düzeyde yüksek ulaştırma talebi olan bir şehirdir. Bu talebin karşılanması her zaman kolay değildir. Ulaştırma alanında uzman kişiler, özellikle zirve saat trafiği, sürücü davranışları, yetersiz mevcut yol kapasitesinin verimsiz kullanılması gibi durumlar üzerine çalışmalar yürütmektedir.

Bu çalışmada İstanbul Büyükşehir Belediyesi'nin kullandığı 6 adet mikrodalga radar algıyıcıdan (sensör) alınan 2011 – 2014 yılları arasında toplamda 4 yılın Temmuz ve Ağustos aylarının günlük trafik verileri kullanılmıştır.

Kullanılan veriler, istatistiki hız analizleri ile hız değişimleri, şerit bazlı, haftalık, günlük olarak incelenmiştir. Çalışmanın sonucunda, trafik akım hızlarının hangi yol kesitinde, hangi şeritte, hangi hafta gününde nasıl değiştiği araştırılarak elde edilen sonuçlar detaylı bir şekilde açıklanmaktadır.

Ümraniye – Kavacık arasında bulunan otoyol kesitinde konumlandırılmış sensörlerden alınan veriler kullanılarak, serbest hızların dağılımları ortaya konulmuştur.

Ayrıca, şeritler arasındaki maksimum hız farkı ile yol hızı arasındaki ilişki, regresyon analizleri ve grafiklerle gösterilmektedir.

Şeritler arasındaki maksimum hız farkı ile yol akım oranı arasındaki ilişki de yine regresyon analizleri ve grafiklerle açıklanmaktadır.

Çalışmanın kısaca hangi bölümlerden oluştuğu, bölüm içerisinde değinilen konular aşağıda kısaca açıklanmaktadır.

Birinci bölüm, bu çalışmanın kısa bir özetini içermektedir. Bu bölümde tezin amacı, kapsamı, katkısı ve organizasyonu anlatılmaktadır.

Karayolu trafik akım temelleri ikinci bölümde anlatılmakta, trafik akım ölçüleri, trafik akımının değişkenleri, trafik akımının değişkenleri arasındaki temel ilişkiler ve trafik akım değişkenleri ölçümünün kısa özetleri bulunmaktadır. Trafik akım ölçüleri kısmında, zaman – yol grafiği ve zaman – taşıt sayısı grafiği verilmektedir. Trafik akım değişkenleri kısmında, akım, yoğunluk ve hız konularına değinilmiştir. Trafik

akım değişkenleri temel ilişkileri başlığı altında söz konusu ilişkiler grafiklerle sunulmakta, Greenshields, Greenberg, Underwood, Northwestern, Pipes-Munjial ve Drew gibi tek rejimli modeller ile Edie, İki rejimli doğrusal, Değiştirilmiş Greenberg ve Üç rejimli doğrusal gibi çok rejimli modeller gösterilmektedir. Trafik akım değişkenleri ölçümü başlığı altında trafik akım ölçüleri ve değişkenlerinin geleneksel yöntemler ve gelişmiş ve akıllı ölçüm sistemleri ile elde edilmesi anlatılmaktadır.

Tezin üçüncü bölümü kısa bir literatür taramasını içermektedir. Otoyolda serbest hızın zamansal ve mekansal değişimi, hız değişimi ve otoyol trafik sıkışıklığı, kaza öncesi otoyol hızları ve hız değişimleri, değişen hız limitlerinin otoyol trafik akımına etkileri, rasyonel hız limitlerinin uzun dönem hız uyumu ve güvenliğe etkileri, tasarım hızları ve uygulanan hız limitleri arasındaki farkların hız seçimine etkisi gibi konular bu bölümün ana konularıdır.

Bu tezin örnek çalışması dördüncü bölümde anlatılmaktadır. Bu bölümde, çalışma alanının anlatılması, trafik verilerinin anlatılması, veri doğrulama ve hız verilerinin sınıflandırılması konularını içermektedir. Ayrıca, saha gözlemleri hız verileri için sayısal uygulamalar dördüncü bölümün ana konularıdır. Bu bölümde, saha gözlem hız verileri için istatistiksel değerlendirmeleri bulunmaktadır.

Hız verileri iki ana başlık altında analiz edilmiştir: sıkışık olmayan durum ve sıkışık durum. Bu çalışmada, sıkışık ve sıkışık olmayan akımlardaki hız verilerinin betimleyici istatistikleri hesaplanmıştır.

Bu tezin içeriğinde, ayrı ayrı sıkışık ve sıkışık olmayan akımlarda şeritler, haftalar ve hafta günleri değişimlerinin hızlar üzerindeki etkisinin değerlendirmek üzere Kruskal-Wallis (K-W) testleri yapılmıştır.

Bu çalışmada, serbest akım hız bölgesinde şerit ve yol hız verilerinin dağılımını belirlemek için, Kolmogorov-Smirnov (K-S) testleri uygulanmıştır. Analiz edilmiş dağılımlar normal, lognormal, gamma, gumbel, üstel ve tekdüze dağılımlarıdır.

Şeritler arasında maksimum hız farkı ve yol hızı arasındaki ilişkiyi araştırmak adına regresyon analizi yapılmıştır. Bu araştırmalar sıkışık olmayan ve sıkışık durumlarda ayrı olarak yapılmıştır.

Buna ek olarak, sıkışık ve sıkışık olmayan durumlar için şeritler arasında maksimum hız farkı ve yol akım oranı arasındaki ilişki regresyon analizi yapılarak değerlendirilmiştir.

Son bölümde, beşinci bölümde, bu tezin sonuçları verilmiştir. Sıkışık olmayan akım kısmındaki hız verisinin betimleyici istatistikleri, en sol şeridin, hızların ortalamasının en büyük olduğu şerit, en sağ şeridin ise hızların ortalamasının en düşük olduğu şerit sonucunu vermiştir. Ayrıca, Pazar günleri en yüksek hız ortalaması ve en düşük standart sapma olduğu ortaya konulmuştur.

Sıkışık olmayan akım kısmındaki hız verisinin K-W test sonuçları, hızların, şeritler arasında belirgin bir şekilde değiştiğini göstermektedir. Ancak, haftalar ve hafta günleri arasında hız değişimlerinin bu kadar belirgin olmadığı sonucuna ulaşılmıştır. Sıkışık akım kısmındaki hız verisinin K-W test sonuçları, bazı yol kesitlerinde, hızların bir şeritten diğerlerine, bir belirli hafta gününden diğerlerine, ve bir hafta gününden diğerlerine belirgin bir şekilde değişmediğini göstermektedir.

Yol kesitlerindeki 35 adet K-S testi sonuçlarına göre serbest akım hız verilerinin, 20 defa normal dağılıma, 19 defa gamma dağılımına, 18 defa lognormal dağılımına ve 3 defa gumbel dağılımına uyduğu sonucuna ulaşılmıştır. Bununla birlikte, analiz edilen

yerlerden 2 yol kesitinde, serbest akım hız verilerinin haftanın her bir günü için normal dağılıma uyduğu gözlenmiştir.

Ayrıca, şeritlerde yapılan 140 adet K-S testi sonuçlarına göre serbest akım hız verilerinin, 14 defa normal dağılıma, 14 defa gamma dağılımına, 13 defa lognormal dağılımına ve 2 defa gumbel dağılımına uyduğu sonucuna ulaşılmıştır.

Regresyon analizi sonuçları, trafik sıkışıklığının olmadığı ve olduğu alanlarda, analizlerin %50'sinde, şeritler arasında maksimum hız farkı ile yol hızı arasında orta bir ilişki olduğunu göstermektedir.

Trafik sıkışıklığının olmadığı ve olduğu alanlar için yapılan regresyon analizi, analizlerin %30'unda, şeritler arasında maksimum hız farkı ile yol akım oranı arasında orta bir ilişki olduğu sonucu ortaya koymaktadır. Şeritler arasında maksimum hız farkı, yol akım oranı arttıkça azalmaktadır.

1. INTRODUCTION

1.1 Motivation

Speed, beside the density and flow is a fundamental variable of traffic flow. Particularly, speed variable and its variations such as average speed, free flow speed, optimum speed (capacity speed), and acceleration/deceleration play crucial role in road safety and road capacity evaluations. The speed analysis on a basic freeway segment of O-2 in Istanbul shapes up the aim of this thesis.

1.2 Scope of the Thesis

This thesis aims to investigate the change of speed across lanes, weeks and days of week. The investigation is realized for uncongested and congested areas separately.

In the scope of this thesis, an attempt to determine the distribution of speed data is similarly realized.

The relationship between maximum speed difference across lanes and road speed were investigated by using “road speed – maximum speed difference across lanes” diagrams and applying regression analyses. Moreover, “road flow rate – maximum speed difference across lanes” diagrams and regression analyses were used in order to examine the relationship between maximum speed difference across lanes and road flow rate. Both of these investigations were performed at uncongested and congested areas, separately.

1.3 Thesis Contributions

Istanbul is a crowded metropolitan with a remarkable high transportation demand. Compensating this demand is difficult mostly all the time. Engineers specialized in transportation sector, concentrated on congestion issues even face complications stemming from high demand levels at peak hours, aggressive behavior of drivers and mainly inefficient usage of insufficient road infrastructure.

1.4 Thesis Organization

This chapter includes a brief introduction to this thesis. Chapter two discusses about the fundamentals of road traffic flow which mainly contains measures of traffic flow. Chapter three of this study represents a brief literature review. The case study of this thesis is the topic to be focused in chapter four. This chapter encompasses the numerical implementations and statistical evaluations for speed data of field observations. Finally, the conclusions are given in chapter five.

2. FUNDAMENTALS OF ROAD TRAFFIC FLOW

Traffic flow can be characterized by individual vehicles and drivers and their interactions with each other and also geometric characteristics of road segments. Traffic flow characteristics will not be constant all the time because of expected differences and variabilities between vehicles, drivers and road segments. For this reason, traffic flow has a complicated structure. Determining the traffic flow characteristics truly and accurately is an essential requirement in designing, planning, and offering best level of service (LOS) of transportation system.

In order to understand and model the behaviour of traffic flow, many approaches have been developed. Where macroscopic traffic flow modeling approach considers traffic flow as a whole, microscopic approach examines traffic flow on a scale of each vehicle. In addition, in mesoscopic modeling approach, the vehicle dynamics determined by microscopic approach is defined as a function of macroscopic approach.

2.1 Measures of Traffic Flow

Traffic flow measures and variables of traffic flow are explained in this section. Traffic flow measures are space (x), time (t) and traffic unit (n) (vehicle, pedestrian, or cargo). Variables of traffic flow are flow (q), density (k), and speed (u) that derive from traffic flow measures to define the behaviour of traffic flow. First, in this section, traffic flow measures and the ways of obtaining these measures are explained. Then, variables of traffic flow and the methods of obtaining of these variables are discussed. Finally, relationships between traffic flow variables are clarified.

2.1.1 Traffic flow measures

There are three types of data that can be obtained during traffic flow observations. These data are called traffic flow measures. Space (x) (m, km, etc.), time (t) (s, min, h), and traffic unit count (n) are measures that cannot be divided into smaller

components. Traffic flow measures alone, are meaningless and do not provide enough information. In other words, mathematic models can not be produced by using only these measures [1].

2.1.1.1 Time – space diagram

Movements of a traffic unit can be described in cartesian coordinates of space (x) and time (t). A graphical representation of $x(t)$ in the (t, x) plane is a curve which is call as trajectory. In Figure 2.1 horizontal axis represents time (t) and vertical axis represents space (x). As illustrated by two of the curves in Figure 2.1, trajectories provide an intuitive, clear and complete summary of vehicular motion in one dimension. Curve (a1), for example, represents a vehicle that is proceeding in the positive direction, slows down and finally reverses direction. Curve (a2) represents a vehicle that resumes travel in the positive direction after nearly stopping. Curve (a3), however, is not a representation of a trajectory because there is more than one position given for certain t's (e.g. t_0); such a curve is not representation of a (single-valued) function $x(t)$. Valid vehicle trajectories must exhibit one and only one x for every t [2].

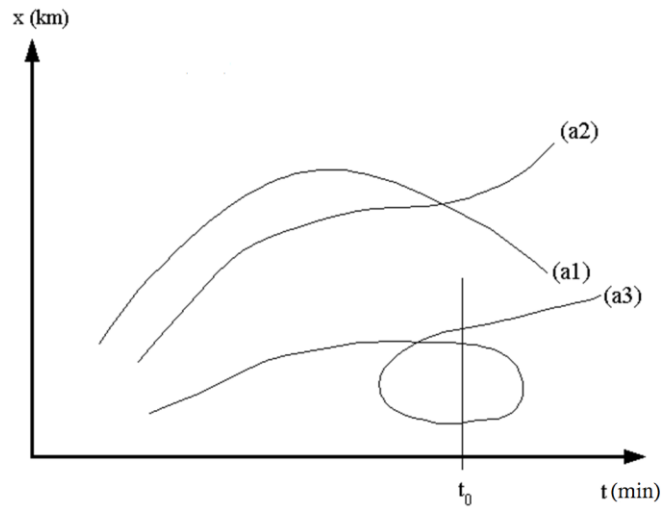


Figure 2.1 : Time – space curves: (a1) and (a2) are vehicle trajectories; (a3) is not [2].

The first and second time derivatives of a vehicle i trajectory (e.g. curve ‘a1’ of Figure 2.1) represent the speed (u_i) and acceleration (a_i) of the vehicle i at time t , respectively; i.e., that $u_i(t) = dx(t)/dt$ and $a_i(t) = d^2x(t)/dt^2$ [2].

Figure 2.2 illustrates the trajectories of some objects traversing a facility (e.g. highway lane, roadway, walkway, conveyor belt) of length L during time interval T ;

these objects may be vehicles, pedestrians or cargo. Each trajectory is assigned an integer label in the ascending order that the object would be seen by a stationary observer. If one object overtakes another, their trajectories may exchange labels, as shown for the fourth and fifth trajectories in the Figure 2.2 [3].

Spacing (s_i) is the distance between successive vehicles (vehicle i and vehicle $i-1$) in a traffic flow, measured from the same point on each vehicle (e.g., front bumper, front axle). Headway (h_i) is the time between successive vehicles (vehicle i and vehicle $i-1$) as they pass a section on a lane or roadway, measured from the same point on each vehicle (e.g., front bumper, front axle) [4]. Spacing (s_i) and headway (h_i) values can be obtained by using time – space ($t - x$) curves and these two mentioned values are used to calculate flow (f) and density (k) variables [3].

Referring to Figure 2.2, the spacing of vehicle 3 at time t_1 , $s_3(t_1)$, is the distance separating vehicle 3 from the next downstream vehicle (vehicle 2). Also, the headway of vehicle 3 at section x_1 , $h_3(x_1)$, is the difference between the arrival times of vehicles 3 and 2 at section x_1 [3].

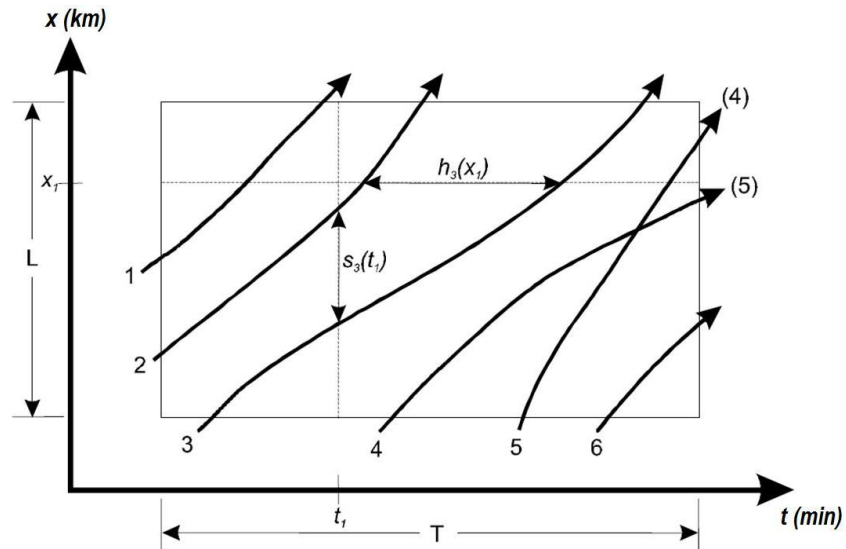


Figure 2.2 : Time – space curves [3].

2.1.1.2 Time – vehicle count diagram

Time – vehicle count ($t - n$) diagram is expression of the number of passing vehicles over a certain section of a road in short time intervals, relating to time (Figure 2.3a). Time – cumulative vehicle count ($t - \sum n$) diagram indicates the cumulative number of passing vehicles over a specified section of a road in short time intervals, relating to time (Figure 2.3b). Drawing time – cumulative vehicle count variations for more

than one road section can leads to find values like number of vehicles and travel time (segment passing time of vehicles) between road sections. Time – vehicle count and time – cumulative vehicle count diagrams can be drawn as histograms like given Figure 2.3.

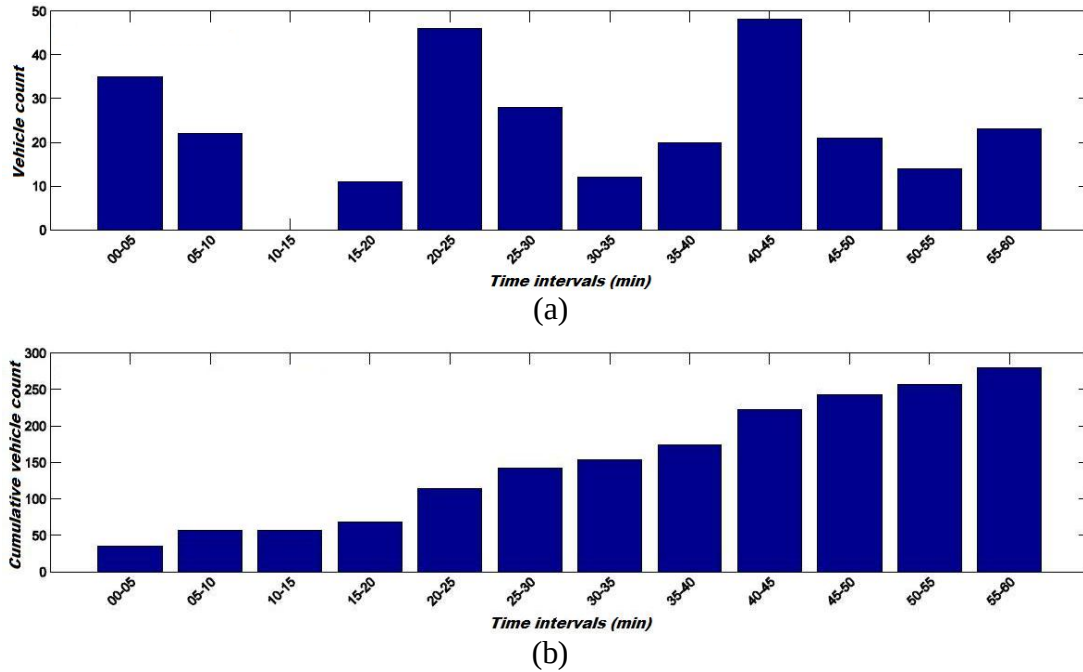


Figure 2.3 : Time – vehicle count and time – cumulative vehicle count diagrams.

As shown in Figure 2.4, cumulative vehicle count function $\sum n(t)$ has been obtained by aggregating cumulative vehicle counts at each instant t similar to Figure 2.3b. Either to easily observe of variations in short time intervals, and to have the feature of ability to do differential calculation, step form $\sum n(t)$ function has been brought to $\sum \tilde{n}(t)$ function form by using interpolation method. This curve ($\sum \tilde{n}(t)$) is in the form of an interpolation curve passing through the crests of every step [2].

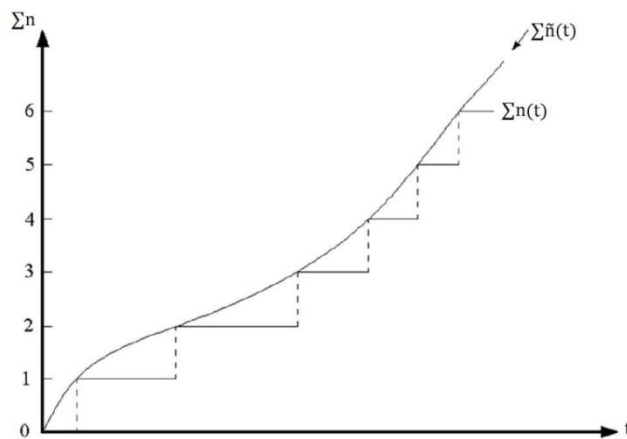


Figure 2.4 : Obtaining cumulative vehicle count function [2].

In order to observe the variations of flow, rescaled cumulative vehicle count curves are drawn. The rescaled cumulative vehicle count values are calculated by $\Sigma n(t) - q_0 t$; where $\Sigma n(t)$ is the cumulative vehicle count at t and q_0 is the reference flow value.

2.1.2 Variables of traffic flow

Since traffic flow measures cannot describe traffic flow at a favorite level, by supposing one of the three measures to take its infinite small value, various variables can be obtained by evaluating the relationship between the other two measures. For instance, when the “space (x)” takes its infinite small value, “flow (q)” variable is obtained from the relationship between traffic unit count (n) and time (t), as shown in Eq. (2.1). Similarly, when the “time (t)” takes its infinite small value, “density (k)” variable is acquired from the relationship between traffic unit count (n) and space (x), as shown in Eq. (2.2). In addition, when the “traffic unit count (n)” takes its infinite small value ($n = 1$), “speed (u)” variable is obtained from the relationship between space (x) and time (t), as shown in Eq. (2.3) [1].

$$x \rightarrow \Delta x \Rightarrow q = \frac{n}{t} \quad (2.1)$$

$$t \rightarrow \Delta t \Rightarrow k = \frac{n}{x} \quad (2.2)$$

$$n = 1 \Rightarrow u = \frac{x}{t} \quad (2.3)$$

In Eq. (2.1) – (2.3) the unit of x is meter, the unit of t is second and the unit of n is vehicle. Therefore the units of q , k and u are veh/s, veh/m and m/s respectively.

2.1.2.1 Flow

Flow (q) is defined as the number of vehicles that pass over a certain lane or road section during unit time (generally assumed as one hour). Flow (q) is often expressed as vehicle per hour (veh/h). There is a direct relationship between flow (q) and headway (h_i). According to Eq. (2.4), total observation time (t) is generated from the sum of the headways (h_i) of every vehicle i . Here, h_i is the headway of vehicle i and n is the number of vehicles [5].

$$t = \sum_{i=1}^n h_i \quad (2.4)$$

As shown in Eq. (2.5), the relationship between flow (q) and headway (h_i) is acquired by using Eq. (2.1) and (2.4). Flow (q) is equal to the reverse of the average headway ($\bar{h}$), as shown in Eq. (2.5) [5].

$$q = \frac{n}{t} = \frac{n}{\sum_{i=1}^n h_i} = \frac{1}{\frac{1}{n} \sum_{i=1}^n h_i} = \frac{1}{\bar{h}} \quad (2.5)$$

In Eq. (2.5) the unit of q is vehicle/second and the unit of $\bar{h}$ is second. If flow will be expressed in veh/h then Eq. (2.5) is expressed as:

$$q = \frac{3600}{\bar{h}} \quad (2.6)$$

The equivalent hourly rate at which vehicles pass over a specified lane or road section during a given time interval of less than 1 hour (usually 15 min) is called “flow rate” [4].

2.1.2.2 Density

Density (k) is the number of vehicles occupying a given unit length (usually 1 km) of a lane or road at a particular instant. Density (k) is generally expressed as vehicles per kilometer (veh/km). As shown in Eq. (2.7), the length of observed road segment (x) is acquired from the sum of the spacings (s_i) of every vehicle i. Here, s_i is the spacing of vehicle i and n is the number of vehicles [5].

$$x = \sum_{i=1}^n s_i \quad (2.7)$$

According to Eq. (2.8), the relationship between density (k) and spacing (s_i) is obtained by using Eq. (2.2) and (2.7). Density (k) is equal to the reverse of the average spacing ($\bar{s}$), as shown in Eq. (2.8) [5].

$$k = \frac{n}{x} = \frac{n}{\sum_{i=1}^n s_i} = \frac{1}{\frac{1}{n} \sum_{i=1}^n s_i} = \frac{1}{\bar{s}} \quad (2.8)$$

In Eq. (2.8) the unit of k is vehicle/meter and the unit of $\bar{s}$ is meter. If density will be expressed in veh/km then the Eq. (2.8) becomes:

$$k = \frac{1000}{s} \quad (2.9)$$

As measurement of density (k) is difficult, a more appropriate variable which is called “occupancy (o)” is defined instead of density (k) in traffic engineering. Occupancy can be defined relating to the length or the time. Occupancy which is related to the length can be defined as the ratio of the total length of vehicles in a road (or lane) to the given length of a road (or lane) at a particular instant. Occupancy which is related to time (o), is defined as the proportion of total time that a traffic sensor is occupied by all vehicles in a defined total observation time period (t), as shown in Eq. (2.10). Here, t_i is the time period that a traffic sensor is occupied by a vehicle i and n is the number of vehicles. Occupancy is dimensionless variable [5].

$$o = \frac{\sum_{i=1}^n t_i}{t} \quad (2.10)$$

The relationship between density and occupancy is represented by Eq. (2.11). In this equation, n is the number of vehicles pass the detector during t, L_i is the summed length of detection zone and the length of vehicle i. Here, it is assumed that each vehicle i has constant speed v_i over the distance L_i [5].

$$k = o \times \left[\frac{\sum_{i=1}^n \frac{1}{v_i}}{\sum_{i=1}^n \frac{L_i}{v_i}} \right] \quad (2.11)$$

2.1.2.3 Speed

Speed (v) is defined as the displacement of a traffic unit with respect to time. Speed (v) is generally expressed as kilometers per hour (km/h) or meters per second (m/s). This variable can be determined in many different ways such as spot speed, travel speed, and running speed. Spot speed is the instantaneous speed of a vehicle at a certain location of a road. Spot speed can be computed from time – space (t – x) curves by dx/dt . Travel speed is obtained by total taken distance divided by total travel time including stopped times. Running speed is acquired by total taken distance divided by total travel time by excluding stopped times [4].

There are different definitions for calculating value of average speed. The first definition is “time mean speed” value ($\bar{u}_{tms}$), which is equal to the arithmetic mean of spot speeds of single vehicles, as shown in Eq. (2.12). In this equation, v_i is the spot speed of a vehicle i . Therefore, it is meaningful to calculate the arithmetic mean of spot speeds of single vehicles. Here, n is the number of vehicles [6].

$$\bar{u}_{tms} = \frac{1}{n} \sum_{i=1}^n v_i \quad (2.12)$$

Another definition for average speed is “space mean speed” value ($\bar{u}_{sms}$), which is equal to the harmonic mean of spot speeds of single vehicles, as shown in Eq. (2.13). In this equation, v_i is the spot speed of a vehicle i . Space mean speed ($\bar{u}_{sms}$) is accepted as the traffic flow speed. In traffic engineering studies, the most important factor is space mean speed values. In Eq. (2.13), n is the number of vehicles [6].

$$\bar{u}_{sms} = \frac{1}{\frac{1}{n} \sum_{i=1}^n \frac{1}{v_i}} \quad (2.13)$$

2.1.3 Fundamental relationships of traffic flow variables

In order to define the traffic flow, the base relationship between variables of traffic flow, is given in Eq. (2.14) [1].

$$q = u.k \quad (2.14)$$

Initial study on these three flow variables was realized by Greenshield in 1935. If there is not any constraint or obstacle on the road, maximum speed that traffic flow can achieve is called “free-flow speed (u_f)”. To access to free-flow speed (u_f) there should be very few vehicles on the road and also vehicles should not affect each other. Theoretically, free-flow speed (u_f) is the speed (u) when density (k) is zero; that is when no vehicles are present on the road. On the other hand, when the road is full of vehicles, speed on the road is accepted as zero. In this case, speed of vehicles will be zero and traffic flow appears to be standing with maximum density which is named as “jam density (k_j)”. The speed and density at which maximum flow can be observed are named as optimum speed (u_{opt}) and optimum density (k_{opt}).

respectively. u_{opt} and k_{opt} determine the boundary of uncongested (undersaturated) and congested (oversaturated) traffic flow areas. The relationships between 3 traffic variables, developed by greenshield is given in Figure 2.5 [1].

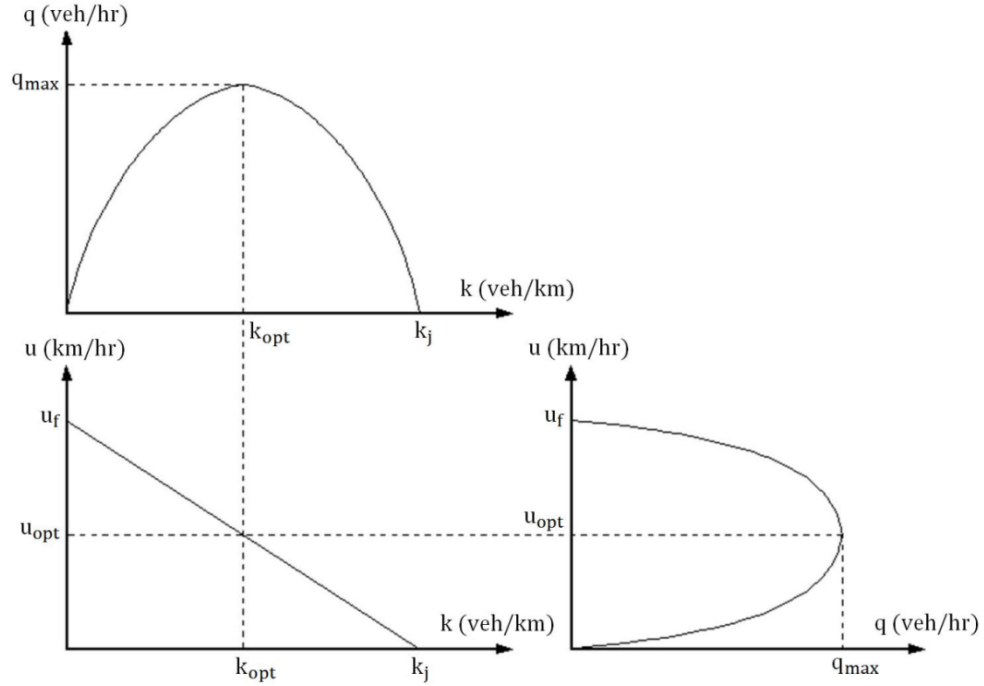


Figure 2.5 : The relations between the fundamental curves [1].

Over the years a number of single-regime models have been proposed by Greenshields (1935), Greenberg (1959), Underwood (1961), Northwestern (1967), Pipes-Munjal (1967) and Drew (1968). These density-speed relationships are given in Table 2.1 [1].

Table 2.1 : Single-regime models.

Model	Function	Model	Function
Greenshields (1935)	$u = u_f \cdot \left(1 - \frac{k}{k_j}\right)$	Northwestern (1967)	$u = u_f \cdot e^{-\frac{1}{2} \left(\frac{k}{k_{opt}}\right)^2}$
Greenberg (1959)	$u = u_{opt} \cdot \ln\left(\frac{k_j}{k}\right)$	Pipes-Munjal (1967)	$u = u_f \cdot \left[1 - \left(\frac{k}{k_j}\right)^n\right]$
Underwood (1961)	$u = u_f \cdot e^{-\frac{k}{k_{opt}}}$	Drew (1968)	$u = u_f \cdot \left[1 - \left(\frac{k}{k_j}\right)^{\frac{n+1}{2}}\right]$

Multi-regime models attempted to improve on earlier models by considering two or three separate regimes. These density-speed relationships are shown in Table 2.2 [1].

Table 2.2 : Multi-regime models.

Model	Free flow regime	Transitional flow regime	Congested flow regime
Edie (1961)	$u = 54.9e^{-\frac{k}{1639}}$ ($k \leq 50$)	–	$u = 26.8 \ln\left(\frac{162.5}{k}\right)$ ($k \geq 50$)
Two regime linear (1967)	$u = 60.9 - 0.515k$ ($k \leq 65$)	–	$u = 40 - 0.265k$ ($k \geq 65$)
Modified Greenberg (1967)	$u = 48$ ($k \leq 35$)	–	$u = 32 \ln\left(\frac{145.5}{k}\right)$ ($k \geq 35$)
Three regime linear (1967)	$u = 50 - 0.098k$ ($k \leq 40$)	$u = 81.4 - 0.913k$ ($40 \leq k \leq 65$)	$u = 40 - 0.265k$ ($k \geq 65$)

2.2 Measuring Variables of Traffic Flow

Methods for measuring variables of traffic flow can be divided into two groups. The first one is the conventional methods for obtaining traffic flow measures. The second one is the advanced and intelligent measurement systems.

Conventional methods for obtaining traffic flow measures include passive acoustic array sensors, infrared sensors, magnetic sensors, ultrasonic sensors, video image processors, inductive loop detectors, remote traffic microwave sensors, and traditional test vehicle (floating car) technique [7].

Advanced and intelligent measurement systems consist of electronic distance-measuring instrument, electronic license plate matching, cellular phone tracking, automatic vehicle identification, automatic vehicle location, video imaging, global positioning systems, Bluetooth traffic monitoring technology, radio frequency identification, and floating car data [8].

The remote traffic microwave sensor (RTMS) is a traffic sensor which uses microwave signals to detect vehicles. The remote traffic microwave sensors (RTMSs) that transmit a continuous wave (CW) Doppler waveform cannot detect stopped vehicles. The RTMSs that transmit a frequency modulated continuous wave (FMCW) can easily detect stationary objects as they modulate the transmitted frequency. The data supplied by RTMSs are vehicle passage, presence, count, occupancy, speed, vehicle length grouped into several length bins. RTMSs perform well in all weather conditions. RTMS can be set up either in a side-fired or forward-looking set-up. When the RTMS set up as a side-fired position, one detector can monitor up to eight lanes for obtaining traffic flow data. In side-fired position, RTMS measures speed of a vehicle from the average length of that vehicle and the amount of time spent in a detection zone. In forward-looking set-up, there are three detection zones lining up in one lane which are forming a speed trap. In forward-looking set-up, speed and vehicle length measurements are much more accurate compared to side-fired set-up, but one RTMS per lane is required for forward-looking set-up [7].

3. LITERATURE REVIEW

Garber and Gadiraju (1989) investigated how differences in design speeds and posted speed limits influence speed choices. They found minimal speed variation (with speed standard deviations on the order of 7.55 mph) when posted speed limits were 10 mph below design speeds, and essentially constant speed variation, regardless of the difference in posted and design speeds. They also found that drivers chose higher speeds on roadways with better geometric design, irrespective of posted speed limits, and concluded that higher speeds do not necessarily result in higher crash rates, whereas higher speed variation does [9].

Stewart et al. (2005) presented a statistical analysis of the temporal and spatial variability of free flow speed along a freeway segment in Orlando, Florida. In this study, the purpose was to ascertain if there were statistically significant differences in free flow speed estimates from one day to the next or from one location to the next [10].

Loop detectors measured and logged the flow, occupancy, and flow speed for each lane at 30 second intervals along the freeway segment. Of particular interest to this study was the fact that the free flow speed, which theoretically occurs when the volume is 0, can reliably be extrapolated from the near linear uncongested portion of the speed-flow curve [10].

The free flow speed estimates were generated at each station in each day of this study by using a heuristic curve fitting program [11]. The free flow speed estimates showed that the free flow speed is much more spatially dependent than temporally dependent [10].

Series of Analyses of Variance (ANOVA) was carried out for the free flow speeds data set. The results of one-way ANOVAs revealed that the free flow speed was not significantly different from one day to the next but the free flow speed varied significantly from one location to the next. The results of a two-way ANOVA

indicated that both the calendar date factor and location factor were statistically significant. Therefore, when specifying speed-flow relationships for this freeway it would therefore appear that it is more important that a different relationship be developed for each location along the route than for each separate day [10].

The results of the other ANOVAs indicated that location factor was statistically significant in all cases, day-of-the-week factor was not statistically different in only few cases, but day-of-the-midweek factor was not statistically significant in some cases. This would suggest that it is not possible to obtain a representative estimate of the free flow speed at a specific location by only gathering data on one day of the week. Moreover, it is possible to obtain a location specific measure of free flow speed for the mid-week period [10].

It was therefore recommended that in the analysis of freeways, location specific free flow speeds must be estimated first. Subsequently, day-of-the-week specific adjustments may be made, but these will have a much smaller effect [10].

Ko et al. (2006) investigated the characteristics of speed variation obtained from speed profiles of GPS-equipped instrumented vehicles on four freeway segments in Atlanta, Georgia. Of particular interest in this study was the examination of the relationship between acceleration noise and the level of traffic congestion on freeway segments. The data employed in this study consists of second-by-second speed data obtained from GPS-equipped instrumented vehicles and traffic density data obtained from video detection system (VDS) cameras [12].

The relationships among speed variation measures were analyzed using correlation coefficients, i.e., the measure of the linear association between two variables. These measures of speed variation are standard deviation of speed, the coefficient of variation, total absolute speed difference, and acceleration noise [12,13]. Acceleration noise, defined as the root mean square deviation of the vehicle acceleration (i.e. standard deviation), was first proposed to characterize the driver-car-road complex nearly five decades ago [14]. In this study, the authors computed acceleration noise from the root mean square of vehicle acceleration (the deviation around an acceleration of zero) [12]. Among the speed variation measures, acceleration noise has been most widely studied to describe traffic conditions. For example, an attempt was made to relate acceleration noise to freeway level of service

using the energy-momentum concept [15], and a more recent study utilized acceleration noise as a traffic congestion measure [16].

The results of analyses showed that speed variation measures are generally highly correlated with each other, with high correlation coefficients values (near to 1). This study led to the initial observation that acceleration noise seems to provide additional information about a trip that may not be revealed by speed alone. The results of this study showed that, in general, acceleration noise increases as density increases [12].

It is concluded that a combined application of average speed with speed variation may provide an improved description of traffic flow quality than the mere use of average speed [12].

Kockelman et al. (2007) investigated freeway speeds and speed variations preceding crashes, within and across lanes. The results of this study suggested that higher traffic densities result in reducing travel speeds, generally moderating speed variation, lower within lane average speeds and higher within lane speed variation, while producing lower across lane speeds (road section average speeds) and speed variation, and lower overall speed variations. Also, more lanes resulted in higher within lane average speeds and road section average speeds (even higher than suggested by the Highway Capacity Manual) [17]. Greater within lane speed variations occurred in the right-side lanes and highest within lane speed variations was found in the far right-side lane. Lowest within lane speed variations was found in the far left-side lane. There was an obvious anticipation of higher speeds on higher design speed facilities/sections, and this effect was discerned in the empirical results. Within lane, across lane, and total speed variations also rose with design speeds. Left-side lanes exhibited the higher within lane average speeds. The lowest within lane average speeds arose in the next-to-far-right-side lane and the far-left-side lane boasted the highest within lane average speeds. The results also indicated that higher within lane speed variability accompanies higher within lane average speeds [18].

Papageorgiou et al. (2008) studied the effects of variable speed limits on motorways traffic flow characteristics in Europe. In this study loop detectors data which placed every 500 meters along 6 lane freeway were collected. This data contained occupancy, flow, and speed for two different time periods (May 2005 to October 2005 and January 2006 to May 2006). Variable Speed Limits (VSL) control system

is used that determines in real time the speed limits of this motorway stretch by providing appropriate displays to the drivers via Variable Message Signs (VMS) [19].

Since the main goal of the investigation was to examine whether the speed limits modify the shape of the flow-occupancy diagram, curve-fitting methods were used to analyze the effect of speed limits [19].

These are the main conclusion of this study:

- It was found that VSL decrease the slope of the flow-occupancy diagram at under critical (uncongested) conditions; shift the critical (optimum) occupancy to higher values; and enable higher flows at the same occupancy values in over critical (congested) conditions. Moreover, the smaller the imposed speed limit has the effect of the larger the decrease in the slope of the flow-occupancy diagram.
- The speed limit of 50 mph was found to be the main contributor to modified aggregate traffic flow behavior that could be exploited towards more efficient traffic flow. The 60 mph VSL was found to have a moderate impact; while the 40 mph VSL could be used at high occupancies in the interest of traffic safety rather than traffic flow efficiency.
- On rainy days, the non-VSL flow capacity and the critical (optimum) speed are reduced by some 10%. The same quantities were observed to change from day to day (even for the same location) without any obvious reason (stochastic effects) [19].

A primary means of regulating travel speeds on roads is through the posting of speed limits. Speed limits are intended to provide guidance on the safe travel speed for the roadway while simultaneously providing reasonable travel times for drivers [20]. An appropriately set speed limit could improve safety by informing drivers of the safe speed on the road. Speed limits can also reduce the standard deviation of speeds by providing drivers with a common reference point for selecting their desired speeds. Despite the efforts of transportation engineers and law enforcement, ensuring compliance with posted speed limits is sometimes challenging. In other words, while speed limits can play an important role in improving highway safety, simply posting speed limits does not guarantee that drivers will comply with them. Compliance is

often associated with drivers' perception of the appropriateness of the posted speed limit, as well as the threat of receiving a citation if they are exceeding the limit [21].

Son et al. (2009) investigated the long term speed compliance and safety impacts of rational speed limits in Virginia. In this study in order to enhance the safety of highway, a coordinated approach that includes public information and education (PI&E), enforcement and properly set of speed limits (rational speed limit-RSL) was utilized. A RSL is a speed limit that is set based on sound engineering practice and supplemented by a coordinated campaign of PI&E and enforcement. Study site were restricted to two separate freeway segments in the Virginia. Speed data, crash data, and driver attitudes were evaluated [21].

In this project, speed limits were increased from 55 to 65 mph on two limited access freeways. Prior to the increase in speed limits, there was widespread noncompliance with the 55 mph speed limit and the survey showed that the 55 mph limit had little credibility with drivers. An increased enforcement and PI&E campaign were implemented at both sites for between 12 and 15 months following the increase in speed limit. The results of this study showed some very promising results, including:

- Not surprisingly, average and 85th percentile speeds increased immediately after the speed limit was raised. The average increase was between 1.7 and 4.3 mph, even though the speed limit was increased by 10 mph. Driver compliance with the speed limit increased substantially, and the survey results indicated that drivers strongly supported the increase in the speed limit.
- There were no significant increases in speed or noncompliance with the speed limit following the end of the increased enforcement and PI&E campaigns at the sites.
- The standard deviation of speeds was fairly consistent throughout the before and after periods, which suggests that crash likelihood was not increased due to the increased posted speed limit [21].

4. CASE STUDY

In the following sections, description of field area and traffic data, data validation, categorization of speed data, the analysis of speed data at uncongested and congested flow areas, the distribution of free flow speed, “road speed – maximum speed difference across lanes” relation, and “road flow rate – maximum speed difference across lanes” relation are explained.

4.1 Description of Field Area

In this study, a freeway segment has been selected for numerical analyses. As shown in Figure 4.1, this study stretch is a part of Istanbul O-2 Freeway and is located on the Asian side of Istanbul. O-2 is the freeway in Istanbul that connects European and Asian parts via Fatih Sultan Mehmet (FSM) Bridge.



Figure 4.1 : Istanbul highway network and study stretch.

This study stretch has been analyzed in both directions of O-2 freeway. The first direction (Direction 1) of this study stretch starts after Ümraniye Interchange and ends up before Kavacık Interchange (Ümraniye-Kavacık direction). Furthermore, this direction continues towards FSM Bridge and connects Asian side of Istanbul to its European side. The second direction (Direction 2) of this study stretch begins after Kavacık Interchange and ends up before Ümraniye Interchange (Kavacık-Ümraniye direction). This direction is in opposite side of Direction 1. In other words, this direction is along the route that connects the European side of Istanbul to its Asian side by FSM Bridge.

The length of the study stretch is approximately 4800 meters and there are 4 lanes in each direction of the freeway. It should be noticed that there is no merge and diverge in this study stretch. In each direction, the far-right-side lane and the next-to-far-right-side lane were named Lane 1 and Lane 2, respectively. Similarly, in each direction, the far-left-side lane and the next-to-far-left-side lane were named Lane 4 and Lane 3, respectively. The identification of lanes can be seen in Figure 4.2.

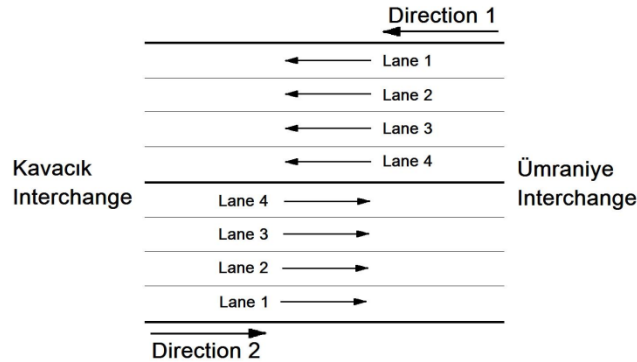


Figure 4.2 : Identification of lanes at study area.

In this study stretch, three remote traffic microwave sensors (RTMSs) have been selected to be analyzed in either Direction 1 or Direction 2. The locations of these 6 RTMSs are shown in Figure 4.3. RTMS 326, RTMS 61, and RTMS 329 are located at Direction 1 and RTMS 316, RTMS 65, and RTMS 317 are located at Direction 2. All RTMSs which have been used in this study, collect data for only one direction of the freeway.

The distances between the RTMSs of both directions in this study are shown in Figure 4.4. In Direction 1, the distance between RTMS 326 and RTMS 61 is 3 km and the distance between RTMS 61 and RTMS 329 is 1.8 km. In Direction 2, the

distance between RTMS 316 and RTMS 65 is 1.6 km and the distance between RTMS 65 and RTMS 317 is 2.9 km.

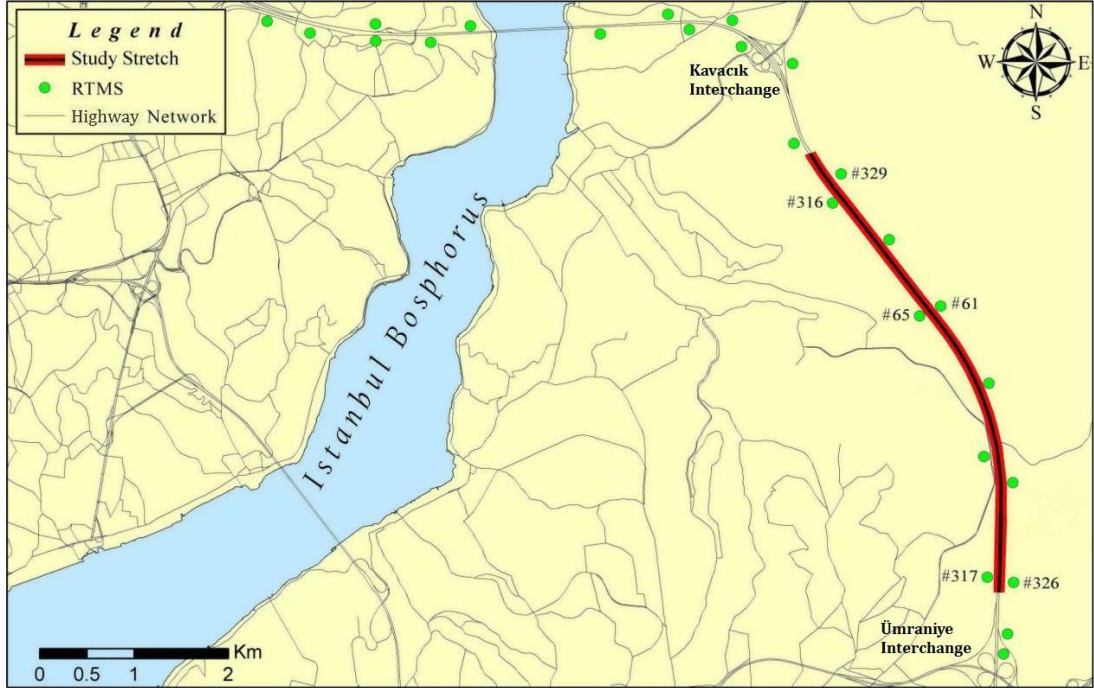


Figure 4.3 : Study stretch and RTMSs positions.

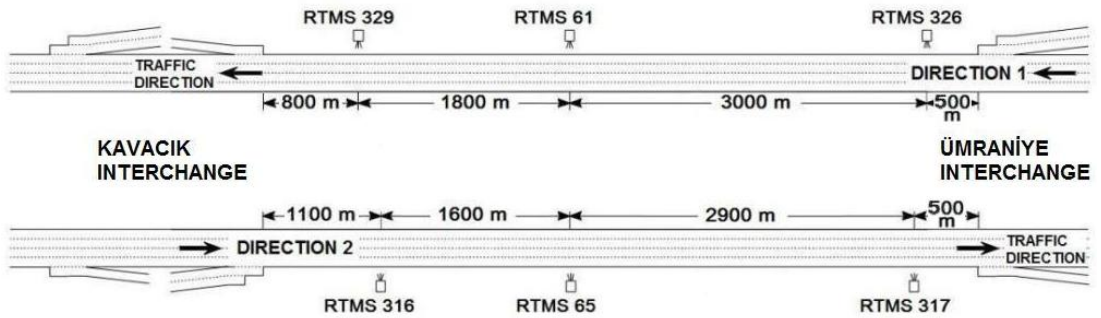


Figure 4.4 : Study segment and the distances between RTMSs.

As the distance between RTMSs and off and on-ramps of interchanges are higher than 450 m, all analyzed RTMS are located at basic freeway segment.

4.2 Description of Traffic Data

As traffic flow is affected by weather conditions, only the data of sunny days are included to analyses. Initially the data of 4 years (2011-2014) July and August are selected. As for each day, 24-hourly data set has been collected in 2-minute time intervals for each of four lanes of each RTMS of this study.

The data obtained by RTMS encompass flow speed, the number of all vehicles, occupancy (in percent), and the number of long vehicles for each lane by their message dates and message times for 2-minute intervals. A sample data of a RTMS is shown in Table 4.1. In this table “S” represents speed, “V” stands for all vehicles (long vehicles and light vehicles) count, “O” is for occupancy (%); “VR”, “VM”, “VL”, “VXL”, and “VXXL” represent long vehicles count in different classifications.

The road speed (S_R) is calculated by vehicle count-weighted average of the corresponding four lanes speeds in that 2-minute interval, as shown in Eq. (4.1).

$$S_R = \frac{(V1 \times S1) + (V2 \times S2) + (V3 \times S3) + (V4 \times S4)}{V1 + V2 + V3 + V4} \quad (4.1)$$

In this equation, S_R represents the road speed in the 2-minute interval. $V1$, $V2$, $V3$, and $V4$ are the all vehicles counts of the 2-minute interval at Lane 1, Lane 2, Lane 3, and Lane 4, respectively. Similarly, $S1$, $S2$, $S3$, and $S4$ are the lane speed of the 2-minute interval at Lane 1, Lane 2, Lane 3, and Lane 4, respectively.

4.3 Data Validation

In this study, traffic data of 6 aforementioned RTMSs on July and August 2011, 2012, 2013 and 2014 were analyzed. As the RTMSs are not working properly, the data of some time intervals are completely missing. On the other hand, for some time intervals, even though the data are present, there are errors at volume or speed data (some speeds with zero volume or some volumes with 0 km/h or 240 km/h speed). All these time intervals unit errors are excluded from data set. Then, as there is no entry or exit at the analyzed freeway segment, in order to investigate the accuracy of data, at each direction time – cumulative volume diagrams were drawn for analyzed years separately. These diagrams are given in Appendix A.

In each direction of each year, the relative error between the last values of cumulative volumes for each RTMS were calculated. If this error is less than 5%, it is assumed that the RTMSs data are reliable.

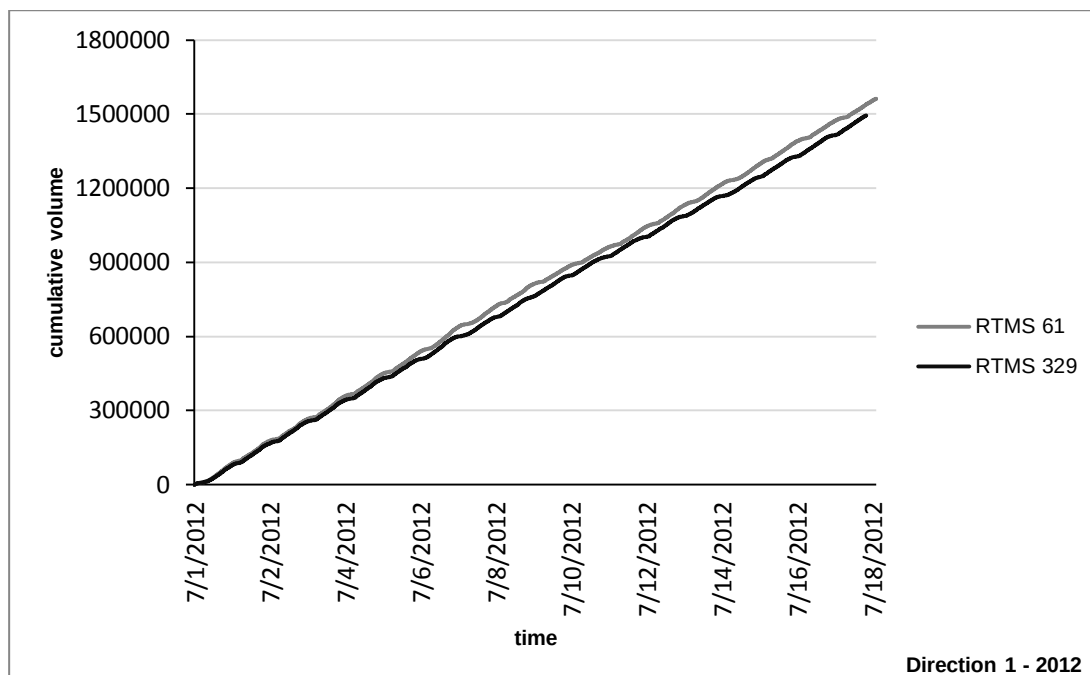
After relative error calculation it is determined that the selected RTMSs in Direction 1 are RTMS 61 and RTMS 329 with 18 days data (July 1st to 18th 2012).

Table 4.1 : A sample data of RTMS.

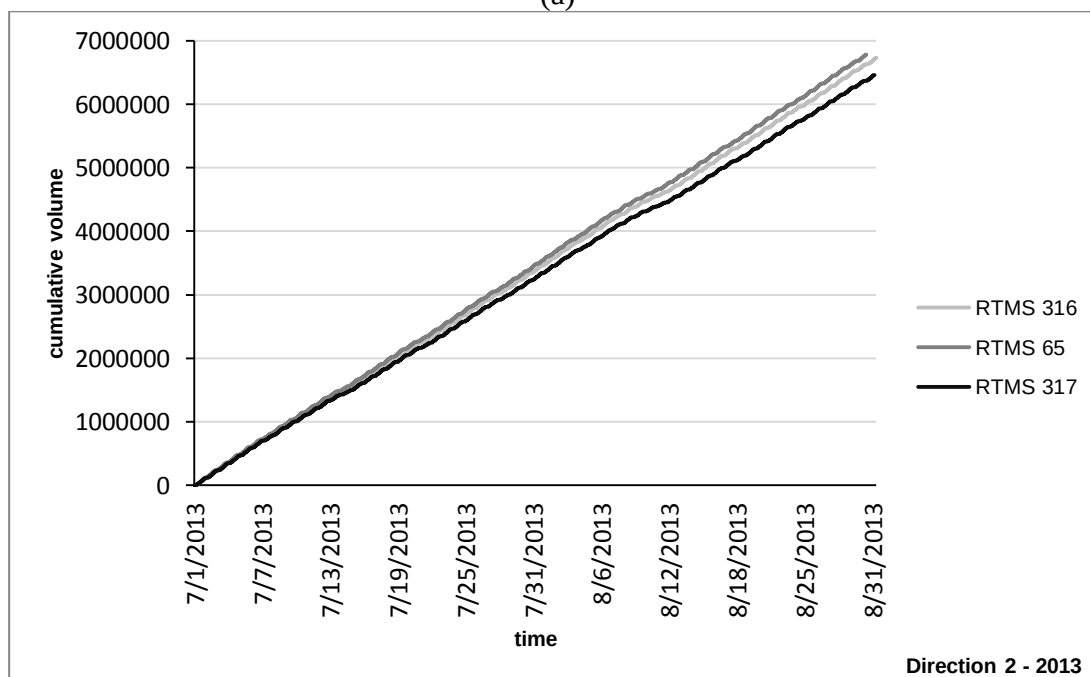
Message Date (M/D/Y)	Message Time	Rtms No	S1	S2	S3	S4	V1	V2	V3	V4	O1	O2	O3	O4	VR1	VR2	VR3	VR4
8/13/2013	12:01:07 AM	317	79	96	96	100	15	18	30	16	6	7	6	2	0	0	6	2
8/13/2013	12:03:06 AM	317	81	93	96	99	13	10	30	19	6	3	5	3	1	2	6	2
8/13/2013	12:05:06 AM	317	81	85	94	102	19	23	35	26	8	7	8	4	1	0	5	1
8/13/2013	12:07:06 AM	317	70	78	85	103	18	17	25	15	7	6	6	2	4	2	2	1
8/13/2013	12:09:07 AM	317	70	78	96	101	13	22	25	19	6	6	5	3	0	3	1	1
8/13/2013	12:11:06 AM	317	74	86	98	102	13	15	23	17	5	5	4	2	1	2	2	1
8/13/2013	12:13:06 AM	317	69	85	95	108	24	23	23	28	10	8	5	4	2	2	5	4
8/13/2013	12:15:07 AM	317	73	87	96	108	11	15	28	16	3	4	5	2	2	2	1	0
8/13/2013	12:17:07 AM	317	79	85	103	106	13	19	28	24	6	7	5	4	0	1	5	4
8/13/2013	12:19:07 AM	317	78	82	101	105	15	23	21	14	6	8	5	2	1	4	3	2
Message Date (M/D/Y)	Message Time	Rtms No	VM1	VM2	VM3	VM4	VL1	VL2	VL3	VL4	VXL1	VXL2	VXL3	VXL4	VXXL1	VXXL2	VXXL3	VXXL4
8/13/2013	12:01:07 AM	317	1	1	0	0	3	3	0	0	5	3	1	0	0	3	0	0
8/13/2013	12:03:06 AM	317	2	0	1	0	6	1	0	1	3	1	0	0	0	1	0	0
8/13/2013	12:05:06 AM	317	1	1	3	0	1	3	3	0	7	4	1	0	1	0	0	0
8/13/2013	12:07:06 AM	317	4	2	5	0	2	4	2	0	0	1	0	0	2	0	0	0
8/13/2013	12:09:07 AM	317	3	4	4	1	2	1	3	0	2	1	0	0	2	0	0	0
8/13/2013	12:11:06 AM	317	0	2	0	0	3	0	3	0	4	4	0	0	0	0	0	0
8/13/2013	12:13:06 AM	317	5	2	0	0	7	5	3	0	2	4	0	0	0	0	0	0
8/13/2013	12:15:07 AM	317	0	1	1	0	1	3	1	0	1	1	0	0	0	0	0	0
8/13/2013	12:17:07 AM	317	1	0	0	0	6	6	1	1	4	5	0	0	0	0	0	0
8/13/2013	12:19:07 AM	317	1	2	4	0	4	4	2	0	2	4	1	0	1	0	0	0

The selected RTMSs in Direction 2 are RTMS 316, RTMS 65, and RTMS 317 with 61 days data (July 1st to August 31st 2013 except August 22th).

Figure 4.5 shows the time – cumulative volume diagrams for selected data and RTMSs of Direction 1 and Direction 2, respectively. In Direction 1, the difference is 4.6%. In Direction 2, the differences are 0.7%, 4.9% and 4.2%.



(a)



(b)

Figure 4.5 : Time – cumulative volume diagrams: (a)Direction 1. (b)Direction 2.

Table 4.2 shows the numbers of used 2-minute speed data in this study.

Table 4.2 : Numbers of used data.

Direction	RTMS No.	Number of Used Data
Direction 1	RTMS 61	64520
	RTMS 329	63540
Direction 2	RTMS 316	216915
	RTMS 65	213625
	RTMS 317	216295

4.4 Categorization of Speed Data

The speed data are analyzed into two main areas: uncongested and congested. The distinguishing of uncongested and congested area are realized by examining “time – speed” and “time – rescaled cumulative flow rate” diagrams.

Congested flow area is defined when following conditions are realized together:

- Speed drops below the optimum speed.
- Speed drop causes a flow drop.
- Speed drop lasts at least 6 minutes.

Queue discharge flow data are included to congested flow area.

Uncongested flow data are obtained after the extraction of congested data from whole data. However, data with less than optimum speed are not included to uncongested flow area.

Figure 4.6 shows the time – speed and time – rescaled cumulative flow rate diagrams for the road section of RTMS 61 on July 5, 2012. As shown in this figure, the congested flow area starts at 6:47:13 AM and ends up at 2:19:13 PM. We can observe the speed drop in this area. Also, because the slope of the rescaled cumulative flow rate curve decreases, the flow decreases in this area.

In this study, as expected, the time – speed and time – rescaled cumulative flow rate diagrams indicated that each of four lanes are congested at generally the same time intervals as the related road section. For example, Figure 4.7 illustrates time – speed and time – rescaled cumulative flow rate diagrams for each lane of RTMS 61 on July 5th, 2012. Similar to the road section, this figure shows that all lanes are congested at the same time interval from 6:47:13 AM to 2:19:13 PM.

At uncongested flow area, it was observed that there is unusual decrease in the speeds after midnight at some RTMSs on some days. These RTMSs are RTMS 329, RTMS 316 and RTMS 317. In other words, there were low values of speed at low

flow values. As there is not any significant change on the flow rate, these speed drops are evaluated as a function of road maintenance work or a malfunction of RTMS. Therefore, these data were removed for each lane and road section of mentioned RTMSs on some days of study. For instance, Figure 4.8 shows the speed decreases after midnight at road section of RTMS 329 on July 4th, 2012. Here, the speed values from 12:58:28 AM to 6:18:29 AM were removed.

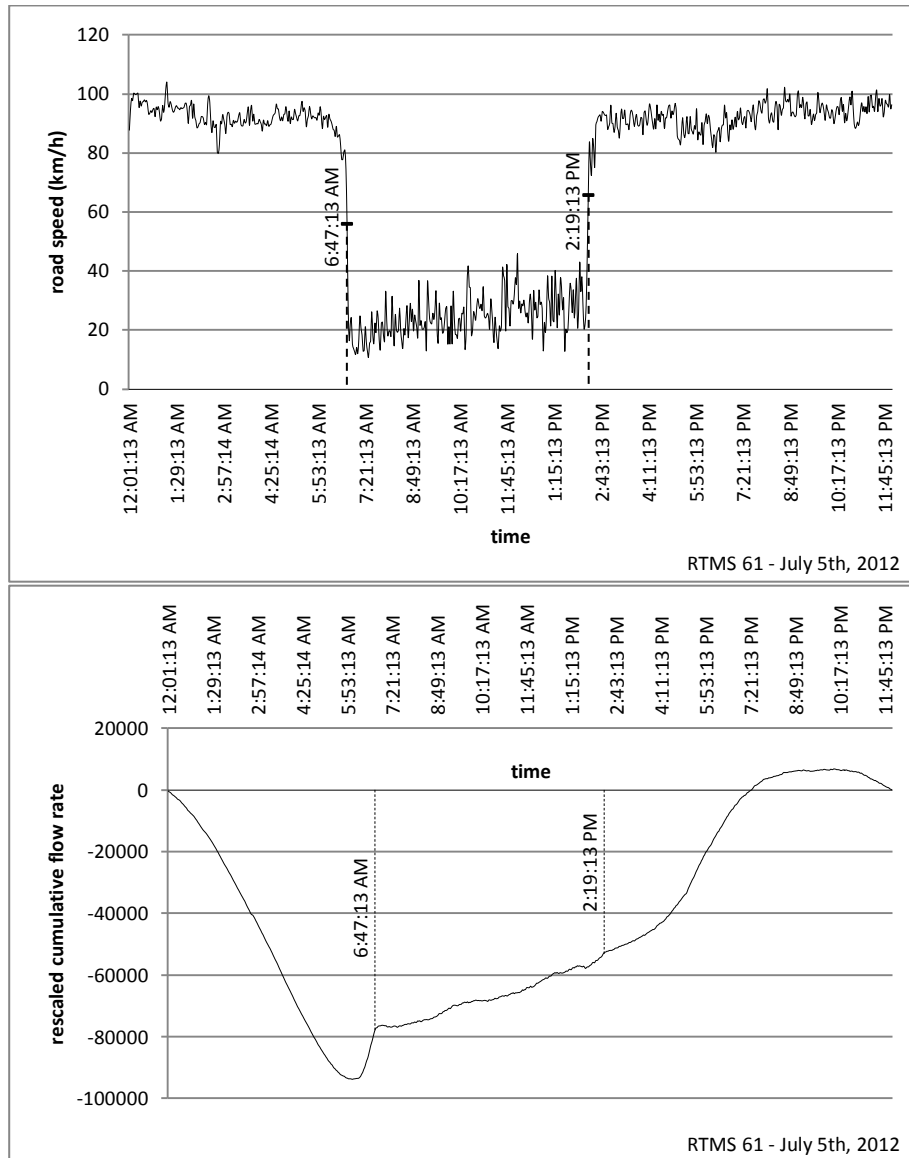


Figure 4.6 : Time – speed and time – rescaled cumulative flow rate diagrams.

Figure 4.9 shows the flow rate – speed diagram for road section of RTMS 316 on all study days. This figure is before deleting the data because of above mentioned reason. The removed data are illustrated in this figure and have been distinguished by surrounding in a ellipse.

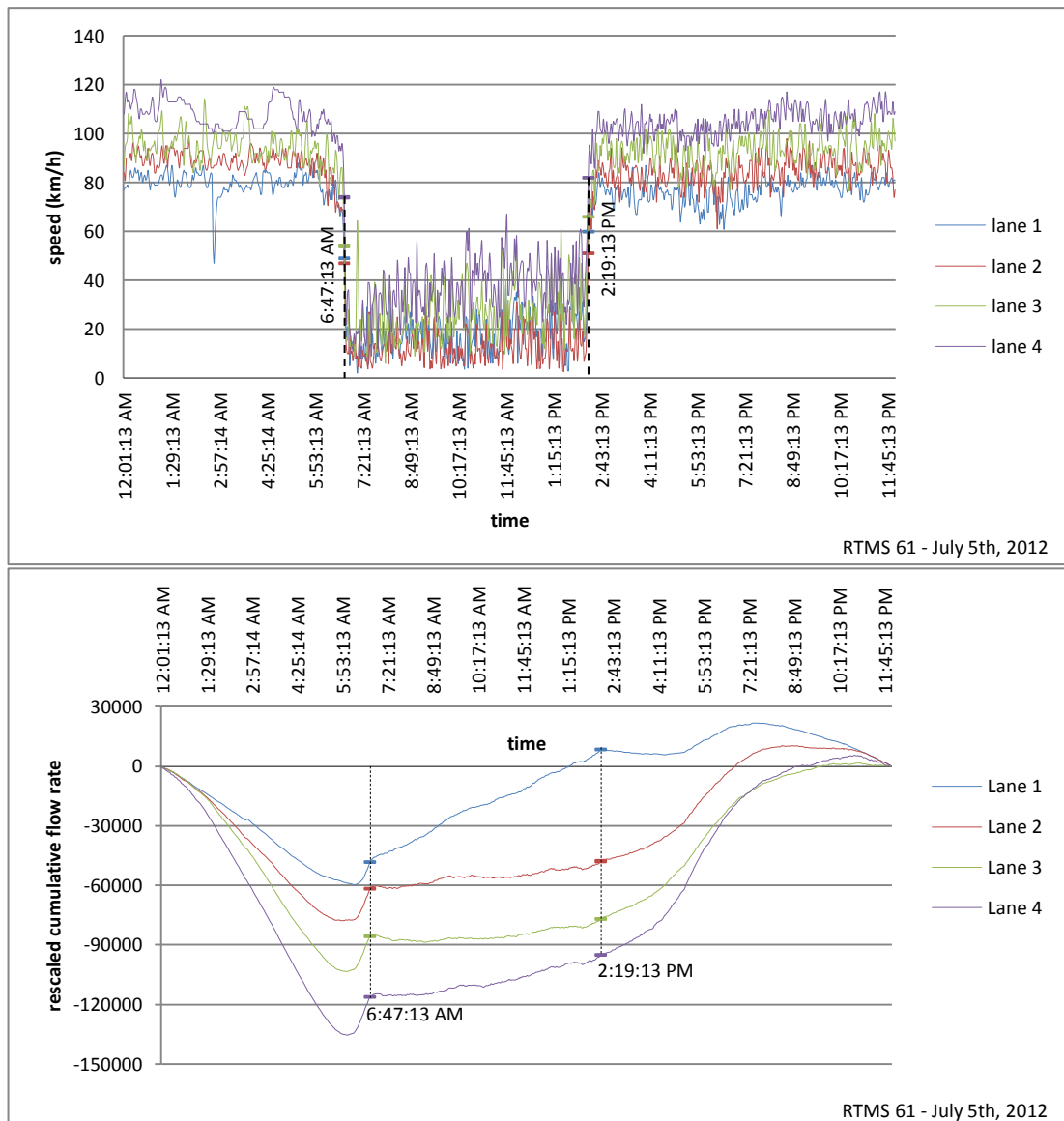


Figure 4.7 : Time – speed and time – rescaled cumulative flow rate diagrams for different lanes.

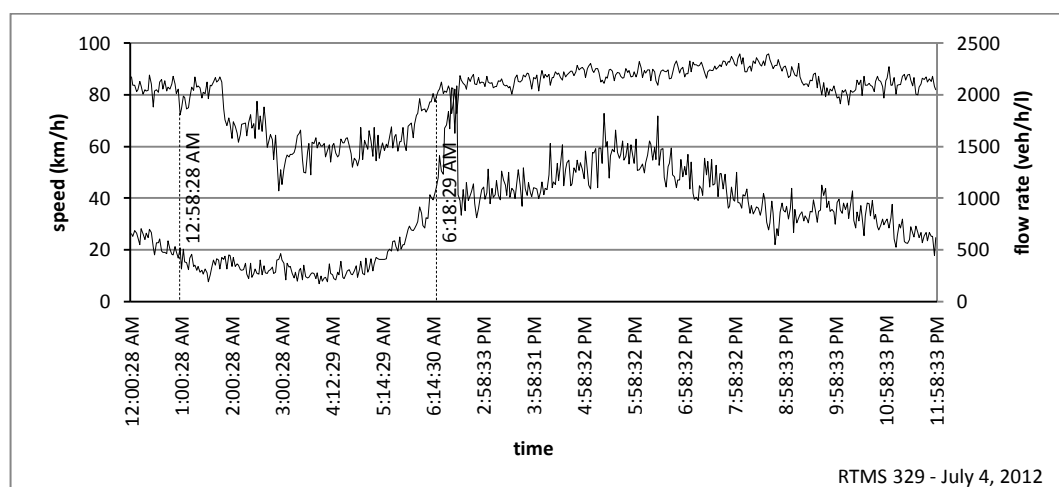


Figure 4.8 : Time – speed and time – flow rate diagrams at uncongested area.

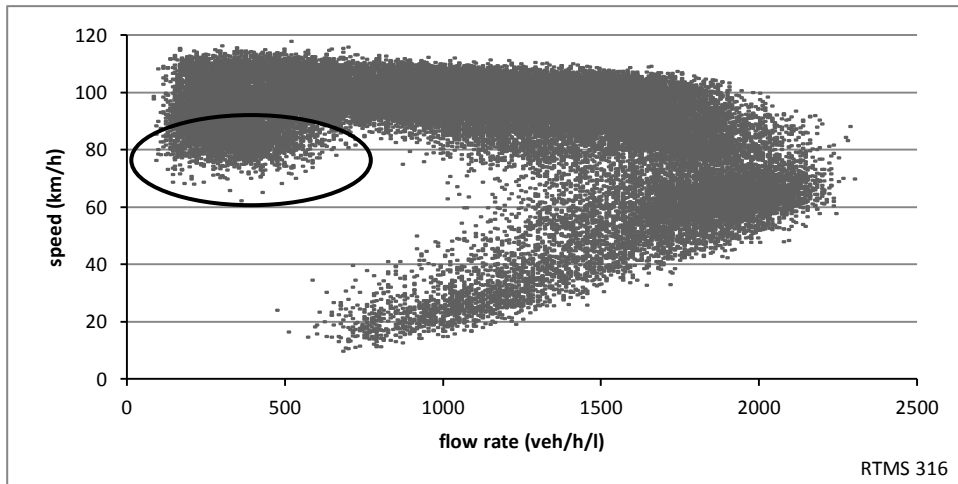


Figure 4.9 : Flow rate – speed diagram.

Figure 4.10 – 4.14 shows the flow rate – speed diagrams for road section of analyzed RTMSs.

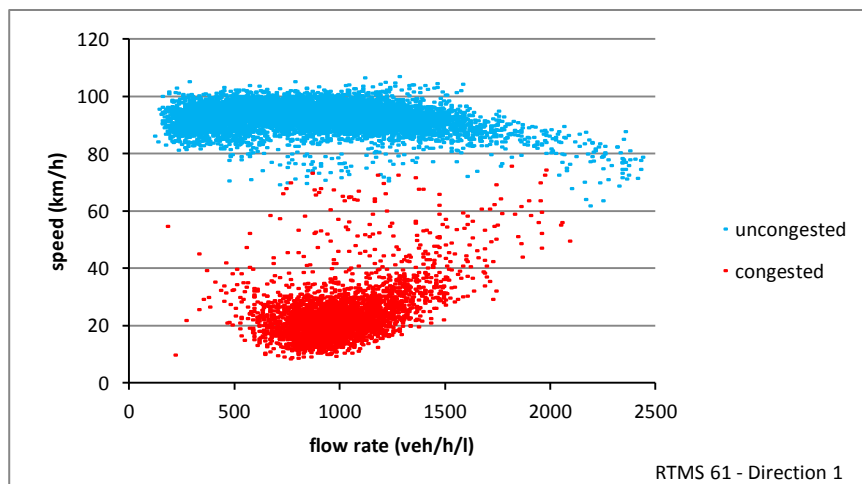


Figure 4.10 : Flow rate – speed diagram of RTMS 61.

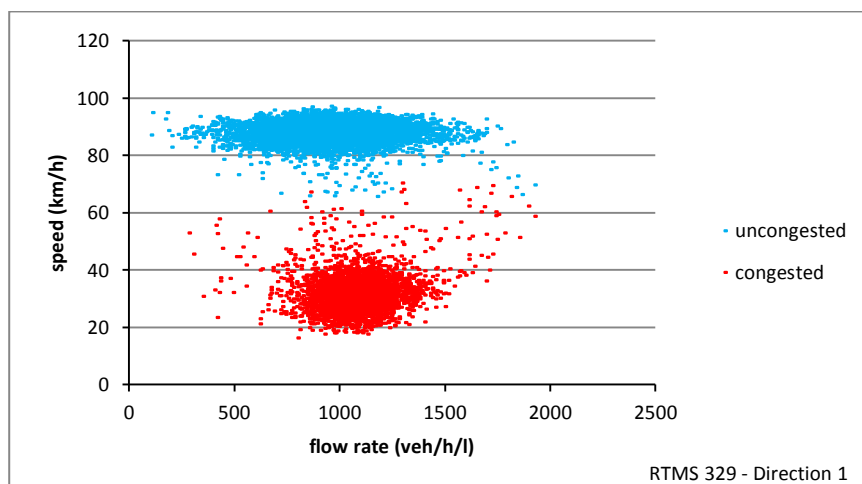


Figure 4.11 : Flow rate – speed diagram of RTMS 329.

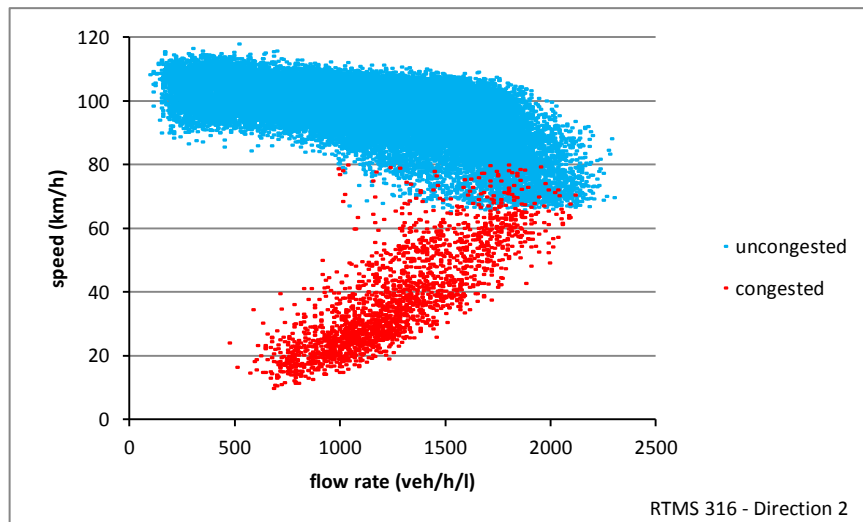


Figure 4.12 : Flow rate – speed diagram of RTMS 316.

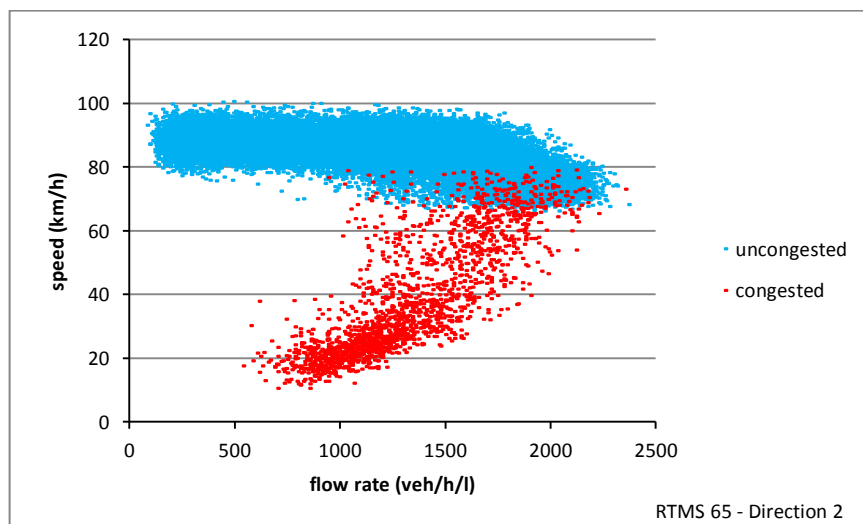


Figure 4.13 : Flow rate – speed diagram of RTMS 65.

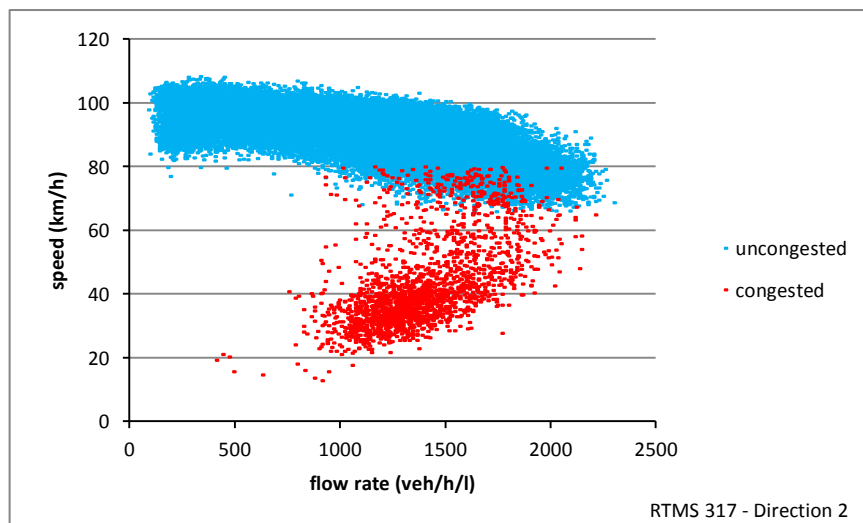


Figure 4.14 : Flow rate – speed diagram of RTMS 317.

4.5 The Analysis of Speed Data at Uncongested Flow Area

In this section, descriptive statistics of speed data at uncongested area are explained. Then, the effects of lanes, weeks, and days on the speeds at uncongested area are evaluated, separately.

4.5.1 Descriptive statistics of speed data at uncongested flow area

The mean and standard deviation were calculated for speed data of uncongested area at each lane and road section of each RTMS on each day of week during all study days and are given in Table 4.3 and 4.4 respectively.

Table 4.3 : Average of speeds (km/h) at uncongested flow area.

Direction	RTMS No.	Lane No.	Mondays	Tuesdays	Wednesdays	Thursdays	Fridays	Saturdays	Sundays
Direction 1	RTMS 61	Lane 1	78.08	78.33	78.63	77.46	78.38	76.55	75.82
		Lane 2	85.20	86.39	86.53	85.59	85.51	84.37	83.88
		Lane 3	92.82	92.51	92.78	93.18	92.02	93.09	94.60
		Lane 4	106.96	106.07	106.49	105.41	105.26	106.21	108.81
		Road Section	92.83	91.69	92.22	92.10	91.69	92.31	93.37
	RTMS 329	Lane 1	68.71	68.25	68.65	68.24	64.63	69.41	72.13
		Lane 2	78.98	77.80	78.61	78.21	75.56	80.47	83.75
		Lane 3	90.49	90.71	90.71	90.47	87.70	90.53	92.53
		Lane 4	105.34	105.78	106.13	105.36	104.40	105.42	106.74
		Road Section	87.26	86.66	86.85	86.97	84.75	88.24	90.26
Direction 2	RTMS 316	Lane 1	82.22	80.72	81.40	83.41	83.47	84.43	89.56
		Lane 2	95.29	92.31	93.58	94.32	95.43	98.00	105.82
		Lane 3	96.84	94.16	94.80	94.65	95.90	98.02	103.89
		Lane 4	97.85	95.51	95.90	95.64	96.75	98.89	103.39
		Road Section	94.81	92.33	93.05	93.42	94.43	96.53	102.41
	RTMS 65	Lane 1	76.17	76.54	76.10	75.70	75.64	75.69	75.61
		Lane 2	84.32	84.95	84.92	84.28	84.12	83.94	82.69
		Lane 3	86.28	85.74	86.17	86.13	86.33	86.74	89.70
		Lane 4	87.27	85.34	85.48	86.13	87.17	88.26	94.82
		Road Section	84.85	84.41	84.60	84.52	84.70	85.21	87.84
	RTMS 317	Lane 1	77.95	76.28	76.73	78.04	78.49	79.67	85.33
		Lane 2	85.50	83.29	83.99	85.23	85.61	87.93	95.37
		Lane 3	90.86	88.74	89.51	89.84	90.78	93.21	98.80
		Lane 4	94.94	93.06	93.69	93.71	94.45	96.29	100.75
		Road Section	88.32	86.27	86.90	87.61	88.23	90.32	96.07

Lane 1 and Lane 4 mostly have the lowest and highest average of speeds, respectively. Sundays generally have the highest average of speeds. In Direction 1 and Direction 2, Fridays and Tuesdays mostly have the lowest average of speeds, respectively.

In Direction 2, Lane 1 generally has the lowest standard deviation of speeds. Sundays mostly have the lowest standard deviation of speeds. In Direction 1, Wednesdays generally have the highest standard deviation of speeds.

Table 4.4 : Standard deviation of speeds (km/h) at uncongested flow area.

Direction	RTMS No.	Lane No.	Mondays	Tuesdays	Wednesdays	Thursdays	Fridays	Saturdays	Sundays
Direction 1	RTMS 61	Lane 1	5.34	5.63	6.85	5.68	5.26	5.49	5.45
		Lane 2	5.73	6.34	7.24	5.95	5.72	5.45	5.79
		Lane 3	6.62	6.87	7.24	6.63	6.46	6.14	6.72
		Lane 4	5.33	6.14	6.15	5.83	5.53	5.32	4.42
		Road Section	4.14	4.50	5.11	4.21	4.02	3.58	3.89
	RTMS 329	Lane 1	5.96	6.73	6.97	6.15	6.02	5.10	4.21
		Lane 2	6.15	6.16	6.39	5.98	6.15	4.96	4.30
		Lane 3	4.47	4.22	4.10	3.94	4.67	3.91	3.69
		Lane 4	3.08	2.96	2.57	2.68	3.33	2.46	2.00
		Road Section	3.98	3.93	3.98	3.40	4.01	3.07	2.49
Direction 2	RTMS 316	Lane 1	7.73	7.60	7.95	9.07	8.66	7.73	4.93
		Lane 2	10.08	10.06	11.03	11.17	11.12	10.16	7.67
		Lane 3	9.69	9.77	10.38	9.83	10.16	9.48	7.50
		Lane 4	9.44	10.30	10.64	10.02	10.25	8.83	5.34
		Road Section	8.02	8.33	9.00	8.90	9.07	8.04	5.55
	RTMS 65	Lane 1	5.92	5.89	5.72	5.86	5.83	5.74	5.69
		Lane 2	6.71	7.31	7.38	7.31	7.27	6.09	4.88
		Lane 3	7.61	8.13	8.08	8.25	7.85	7.18	6.18
		Lane 4	9.55	9.08	9.25	9.37	9.67	9.13	8.58
		Road Section	5.59	5.79	5.81	5.85	5.83	5.17	4.22
	RTMS 317	Lane 1	6.19	5.90	6.32	7.55	7.47	6.72	4.98
		Lane 2	7.82	7.68	8.02	9.11	9.01	8.17	6.20
		Lane 3	8.77	8.40	8.82	9.14	9.21	8.55	6.76
		Lane 4	8.73	9.21	9.26	8.94	9.12	8.24	4.91
		Road Section	6.88	6.74	7.12	7.64	7.69	6.92	4.73

4.5.2 The effects of lanes on the speeds at uncongested flow area

The change of flow speeds at uncongested area are investigated according to lanes with the help of Kruskal-Wallis (K-W) test.

K-W test is a distribution free test and can be used to analyze all types of data. Because of this characteristic, K-W test is applied in this study.

This test is applied to compare several independent groups/samples. The null hypothesis is that the samples come from the same continuous population. The alternate hypothesis is that at least one of the populations tends to produce comparatively larger values than the others. In other words, the K-W test, tests for differences between two or more groups/samples. This test evaluates whether the population medians on a dependent variable are the same across all levels of a factor [22].

The pooled data are ranked from the lowest to the highest as if they belong to one sample. If R_i is the sum of the ranks of the data in the i th sample of size n_i and n is the total sum of the k samples, the K-W test statistic (K) is calculated by Eq. (4.2) [22].

Under the null hypothesis that the samples come from the same population, K has an approximate chi-squared distribution with $(k - 1)$ degrees of freedom. The larger values of calculated K by Eq. (4.2) than the critical value of chi-square distribution at specified degree of freedom and level of significance, leads to rejection of the null hypothesis that all the samples are realizations of one population [22].

$$K = \frac{12}{n(n+1)} \sum_{i=1}^k n_i \left[\frac{R_i}{n_i} - \frac{n+1}{2} \right]^2 \quad (4.2)$$

The speed data at uncongested area were grouped by lane for each RTMS and all analyzed days and K-W tests were implemented at 5% level of significance. Four lanes, three adjacent lanes, and paired adjacent lanes were analyzed, respectively.

As shown in Table 4.5, the results of these analyses clarify that the speeds are statistically different ($K > K_{\text{cri.}}$) for all lanes at all RTMSs.

For instance, the value of K-W test statistic is 32979 for four lanes of RTMS 316. This value has been obtained by applying the speed data of four lanes as given in Table 4.6. In this table, each column contains all days speed data of uncongested area in 2-minute intervals. Here, the degree of freedom is 3 and the critical value of K-W test ($K_{\text{cri.}}$) is 7.81.

Table 4.5 : K-W tests for lanes at uncongested area.

RTMS No.	Lane 1,2,3,4		Lane 1,2,3		Lane 2,3,4		Lane 1,2		Lane 2,3		Lane 3,4	
	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}
RTMS 61	28968	7.81	15720	5.99	19526	5.99	6285	3.84	5699	3.84	11119	3.84
RTMS 329	19255		12301		13713		5319		6245		8149	
RTMS 316	32980		26985		413		18630		37		221	
RTMS 65	40041		34626		3906		21542		2690		188	
RTMS 317	46501		28602		13845		12446		4512		2887	

Table 4.6 : Lane speed data (km/h) of uncongested area for RTMS 316.

Lane 1	Lane 2	Lane 3	Lane 4
76	83	72	78
79	84	78	89
80	95	80	89
81	87	80	88
80	88	85	86
82	83	81	89
76	87	91	97
78	94	85	96
79	87	89	96
81	90	95	99
81	91	87	94
77	95	86	92
...	...	...	...
...	...	...	...
...	...	...	...

4.5.3 The effects of weeks on the speeds at uncongested flow area

The road speed data at uncongested area were grouped by same day of weeks for each RTMS and all days of the study. K-W tests were carried out at 5% level of significance.

As shown in Table 4.7, the results of these tests clarify that the speeds are usually statistically different for the same days of weeks. However at some RTMSs, the speed data of the same days of weeks are statistically similar ($K < K_{cri.}$). These RTMSs and days are as follows:

- RTMS 61: Tuesdays, Wednesdays, Thursdays, Fridays and Saturdays
- RTMS 329: Thursdays, Fridays and Saturdays

For instance, the value of K-W test statistic is 106.09 for Tuesdays at RTMS 65. This value has been acquired by using the speed data of Tuesdays as given in Table 4.8. In this table, each column includes daily speed data of uncongested area in 2-minute intervals. Here, the degree of freedom is 8 and the critical value of K-W test is 15.51.

Table 4.7 : K-W tests for same days of weeks at uncongested area.

RTMS No.	Mondays		Tuesdays		Wednesdays		Thursdays		Fridays		Saturdays		Sundays	
	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}
RTMS 61	11.78	5.99	2.64	5.99	4.72	5.99	1.13	3.84	0.51	3.84	3.42	3.84	44.82	5.99
RTMS 329	48.18	5.99	10.31	5.99	6.91	5.99	0.09	3.84	3.48	3.84	3.74	3.84	80.76	5.99
RTMS 316	210.07	15.51	65.52	15.51	500.14	15.51	570.19	14.07	957.66	15.51	1048.13	15.51	627.59	14.07
RTMS 65	137.83	15.51	106.09	15.51	46.71	15.51	95.38	14.07	141.76	15.51	382.86	15.51	99.74	14.07
RTMS 317	192.82	15.51	153.86	15.51	552.01	15.51	673.84	14.07	1279.69	15.51	1025.27	15.51	571.00	14.07

Table 4.8 : Road speed data (km/h) of uncongested area for RTMS 65.

Tuesday 2-Jul-13	Tuesday 9-Jul-13	Tuesday 16-Jul-13	Tuesday 23-Jul-13	Tuesday 30-Jul-13	Tuesday 6-Aug-13	Tuesday 13-Aug-13	Tuesday 20-Aug-13	Tuesday 27-Aug-13
90.12	82.93	86.04	88.36	89.78	83.21	87.53	91.08	78.78
93.32	83.06	83.43	86.44	86.52	88.23	82.50	91.19	83.51
94.35	82.05	82.08	87.30	90.75	82.38	82.49	82.76	81.88
90.20	83.70	82.12	88.34	90.64	83.04	82.80	85.52	83.89
88.07	87.78	83.64	89.18	94.40	81.28	86.86	86.99	85.27
85.41	84.01	87.61	90.99	90.39	87.86	89.02	85.68	86.49
85.30	90.46	87.48	94.21	89.58	82.37	82.65	83.72	86.45
82.58	87.37	84.87	93.41	89.96	83.89	84.93	86.28	83.41
83.90	87.67	79.43	91.45	92.63	84.13	83.36	90.19	83.59
84.99	88.57	79.79	87.52	92.20	92.37	82.89	87.73	84.58
80.66	90.34	79.73	93.84	87.02	90.94	85.99	82.84	82.70
83.18	88.76	81.93	92.19	83.88	82.89	85.60	88.23	85.04
...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...

4.5.4 The effects of days of week on the speeds at uncongested flow area

The road speed data at uncongested area were grouped by day of week for each RTMS and all analyzed days. K-W tests were performed at 5% level of significance.

Initially, seven days of week were compared with K-W test in order to determine the statistical difference of speed data.

Next, week days (Monday to Friday) and weekend days (Saturday and Sunday) were analyzed, separately.

It is often hypothesized that traffic behavior in mid-week period (Tuesday, Wednesday, and Thursday) is different from Monday and Friday. At the next step the comparison between these three mid-week days is realized.

Finally, paired adjacent days of week were analyzed.

The results of K-W tests are given in the Table 4.9.

Table 4.9 : K-W tests for days of week at uncongested area.

Test for	Days	RTMS 61		RTMS 329		RTMS 316		RTMS 65		RTMS 317	
		K	K _{crit.}	K	K _{crit.}	K	K _{crit.}	K	K _{crit.}	K	K _{crit.}
7 days	Monday to Sunday	227.17	12.59	1310.97	12.59	5213.57	12.59	1428.23	12.59	6568.57	12.59
5 days	Monday to Friday	66.50	9.49	175.33	9.49	251.79	9.49	16.61	9.49	277.31	9.49
3 days	Tuesday to Thursday	8.07	5.99	0.88	5.99	28.74	5.99	4.38	5.99	54.58	5.99
2 days	Saturday and Sunday	93.81	3.84	287.08	3.84	1585.35	3.84	703.28	3.84	2040.96	3.84
	Monday and Friday	54.45	3.84	163.90	3.84	4.17	3.84	0.48	3.84	2.24	3.84
	Monday and Tuesday	38.12	3.84	7.64	3.84	211.08	3.84	13.76	3.84	224.10	3.84
	Tuesday and Wednesday	8.05	3.84	0.54	3.84	21.72	3.84	4.40	3.84	21.12	3.84
	Wednesday and Thursday	1.86	3.84	0.01	3.84	0.03	3.84	0.88	3.84	8.81	3.84
	Thursday and Friday	7.01	3.84	97.61	3.84	36.52	3.84	2.89	3.84	18.97	3.84
	Friday and Saturday	10.27	3.84	304.48	3.84	105.04	3.84	7.54	3.84	189.65	3.84
	Sunday and Monday	20.95	3.84	446.63	3.84	2553.05	3.84	760.61	3.84	3348.62	3.84

The K-W tests of analyzed RTMSs show that:

- Daily speed data of 7 days are not coming from the same population. In other word, at least one day data are statistically different than the others. (unfortunately K-W tests do not indicate which day(s) data are different than the others)
- When 5 days speed data (Monday to Friday) are compared, it is not possible to conclude that they are statistically similar.
- Comparing speed data of 3 days (Tuesday to Thursday) shows that they are statistically similar at 40% of RTMSs.
- Saturday and Sunday speed data are statistically different.
- The comparison of speed data of successive days indicates that most similar days are Wednesday and Thursday according to speed at uncongested area. At 4 of analyzed 5 RTMSs, the speeds of these days are statistically similar. This similarity is observed at 40% of RTMSs between Monday and Friday

speed data. Only at 20% of RTMSs Tuesday and Wednesday, Thursday and Friday speed data are coming from the same population.

For instance, the value of K-W test statistic is 1310.97 for Monday to Sunday at RTMS 329 . This value has been obtained by applying the speed data of seven days of week as given in Table 4.10.

In this table, each column consists of Mondays or Tuesdays or ... or Sundays speed data of uncongested area in 2-minute intervals. Here, the degree of freedom is 6 and the critical value of K-W test is 12.59.

Table 4.10 : Road speed data (km/h) of uncongested area for RTMS 329.

Mondays 2,9,16-Jul-12	Tuesdays 3,10,17-Jul-12	Wednesdays 4,11,18-Jul-12	Thursdays 5,12-Jul-12	Fridays 6,13-Jul-12	Saturdays 7,14-Jul-12	Sundays 1,8,15-Jul-12
88.48	88.13	80.91	68.96	67.39	88.17	90.64
90.07	86.81	85.04	75.46	71.94	89.17	88.61
83.90	73.26	86.06	82.44	77.52	88.89	91.10
88.53	86.37	82.33	80.65	76.72	89.21	88.37
85.79	88.46	85.51	84.43	71.92	89.68	89.28
73.05	88.95	81.53	85.45	75.30	86.47	89.15
79.62	88.08	83.00	82.12	81.58	87.54	91.78
82.77	88.44	78.09	80.20	82.76	89.76	88.60
82.89	90.08	87.35	84.01	78.74	88.73	86.42
83.21	90.93	85.58	84.44	83.88	89.69	87.33
85.45	89.20	84.39	84.55	80.85	89.54	89.40
87.58	93.08	83.61	85.48	85.81	88.02	91.26
...	...	...	...	...	...	...
...	...	...	...	...	...	...
...	...	...	...	...	...	...

4.6 The Analysis of Speed Data at Congested Flow Area

In this section, descriptive statistics of speed data at congested area are discussed. Then, the effects of lanes, weeks, and days on the speeds at congested area are examined, separately.

4.6.1 Descriptive statistics of speed data at congested flow area

The mean and standard deviation were calculated for speed data of congested area at each lane and road section of each RTMS on each day of week during all study days and are given in Table 4.11 and 4.12. In these tables, on sundays, no congestion is observed at some RTMSs.

In Direction 1, Lane 4 mostly has the highest average and standard deviation of speeds. In Direction 2, Mondays generally have the highest average of speeds. In Direction 1 and Direction 2, Thursdays and Tuesdays mostly have the lowest standard deviation of speeds, respectively.

Table 4.11 : Average of speeds (km/h) at congested flow area.

Direction	RTMS No.	Lane No.	Mondays	Tuesdays	Wednesdays	Thursdays	Fridays	Saturdays	Sundays
Direction 1	RTMS 61	Lane 1	17.42	16.04	17.59	17.83	20.21	18.31	NC*
		Lane 2	12.43	11.42	12.12	12.49	14.40	12.10	NC*
		Lane 3	26.09	25.78	25.24	25.88	26.73	23.74	NC*
		Lane 4	35.32	34.74	35.45	35.60	37.92	29.51	NC*
		Road Section	23.78	23.13	23.68	23.94	25.73	21.63	NC*
	RTMS 329	Lane 1	14.91	14.18	14.18	14.26	15.03	20.46	25.78
		Lane 2	21.84	21.62	21.19	21.19	21.19	29.33	34.00
		Lane 3	33.73	34.96	33.78	33.91	34.29	40.13	40.89
		Lane 4	54.03	55.67	54.59	53.73	50.94	51.93	60.33
		Road Section	31.79	32.12	31.35	31.52	30.85	35.17	38.88
Direction 2	RTMS 316	Lane 1	37.17	31.90	32.62	31.58	31.34	32.14	NC*
		Lane 2	41.58	37.45	38.02	37.15	35.73	37.27	NC*
		Lane 3	43.75	41.24	39.28	39.55	38.93	39.32	NC*
		Lane 4	44.09	41.36	39.43	40.09	40.39	39.36	NC*
		Road Section	42.01	38.41	37.65	37.44	36.95	37.27	NC*
	RTMS 65	Lane 1	57.53	54.67	55.65	48.90	54.43	54.04	NC*
		Lane 2	37.53	30.87	35.18	29.14	31.73	31.05	NC*
		Lane 3	33.59	28.50	33.97	27.19	28.82	30.28	NC*
		Lane 4	44.37	40.78	43.95	39.22	40.95	39.95	NC*
		Road Section	42.23	37.65	41.34	35.79	37.98	37.72	NC*
	RTMS 317	Lane 1	38.99	34.99	34.79	32.51	35.89	33.23	NC*
		Lane 2	44.80	42.07	39.48	40.11	41.88	40.13	NC*
		Lane 3	48.17	49.16	43.67	47.63	48.64	45.31	NC*
		Lane 4	48.37	48.68	42.95	47.80	47.96	47.89	NC*
		Road Section	45.37	44.18	40.93	42.70	43.95	42.27	NC*

*NC: no congestion

Table 4.12 : Standard deviation of speeds (km/h) at congested flow area.

Direction	RTMS No.	Lane No.	Mondays	Tuesdays	Wednesdays	Thursdays	Fridays	Saturdays	Sundays
Direction 1	RTMS 61	Lane 1	9.64	9.01	10.29	8.60	10.95	9.67	NC*
		Lane 2	9.38	8.26	9.94	7.58	11.80	9.80	NC*
		Lane 3	13.21	12.14	11.86	11.46	13.44	12.38	NC*
		Lane 4	13.49	13.69	13.29	12.72	14.84	15.24	NC*
		Road Section	9.38	8.45	9.12	8.21	11.19	10.17	NC*
	RTMS 329	Lane 1	6.29	5.75	4.81	4.64	5.86	11.40	13.08
		Lane 2	8.48	8.07	7.08	7.55	7.44	12.64	12.41
		Lane 3	11.65	11.71	11.01	10.71	11.59	13.76	10.71
		Lane 4	13.76	13.59	13.26	12.68	13.36	19.05	11.83
		Road Section	6.87	5.91	5.67	5.53	6.74	11.63	10.48
Direction 2	RTMS 316	Lane 1	20.51	16.79	19.37	18.25	17.60	18.90	NC*
		Lane 2	19.99	16.63	18.71	17.87	17.29	17.99	NC*
		Lane 3	17.09	13.73	16.83	16.35	15.71	15.34	NC*
		Lane 4	14.85	12.50	14.80	14.43	13.50	13.89	NC*
		Road Section	17.01	13.70	16.44	15.61	14.87	15.53	NC*
	RTMS 65	Lane 1	15.08	13.28	15.09	16.52	14.73	16.45	NC*
		Lane 2	24.41	21.75	22.75	23.56	23.25	22.61	NC*
		Lane 3	23.13	20.46	22.61	21.69	21.85	23.54	NC*
		Lane 4	19.36	17.53	18.15	18.03	17.63	19.63	NC*
		Road Section	19.08	16.54	17.85	18.10	17.83	18.61	NC*
	RTMS 317	Lane 1	15.72	16.12	16.75	18.05	16.56	18.54	NC*
		Lane 2	14.79	15.44	17.38	16.18	15.31	15.65	NC*
		Lane 3	14.54	13.80	14.97	14.43	14.01	14.73	NC*
		Lane 4	15.04	16.11	16.78	14.99	15.31	15.68	NC*
		Road Section	13.65	14.01	13.80	14.08	13.86	14.55	NC*

*NC: no congestion

4.6.2 The effects of lanes on the speeds at congested flow area

Similar to uncongested data the lane speed at congested area are compared with the help of K-W test. The result of these tests are given in Table 4.13. Only at 2 RTMSs (#316 and #317) the speed at Lane 3 and Lane 4 are statistically similar.

Table 4.13 : K-W tests for lanes at congested area.

RTMS No.	Lane 1,2,3,4		Lane 1,2,3		Lane 2,3,4		Lane 1,2		Lane 2,3		Lane 3,4	
	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}
RTMS 61	5974.78	7.81	2908.27	5.99	4873.66	5.99	839.55	3.84	2561.29	3.84	956.15	3.84
RTMS 329	11420.79		6687.00		7227.34		2472.24		2817.07		3164.01	
RTMS 316	354.98		239.63		59.58		92.79		32.48		2.13	
RTMS 65	1358.77		1162.60		393.56		778.93		8.22		349.85	
RTMS 317	826.98		640.48		219.69		191.86		179.29		0.88	

4.6.3 The effects of weeks on the speeds at congested flow area

K-W test results of the road speeds at the same days of week at congested flow area are given in Table 4.14. The RTMSs and days at which speed data are statistically similar are:

- RTMS 329: Mondays and Tuesdays
- RTMS 317: Mondays and Saturdays

Table 4.14 : K-W tests for same days of weeks at congested area.

RTMS No.	Mondays		Tuesdays		Wednesdays		Thursdays		Fridays		Saturdays		Sundays	
	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}	K	K _{cri.}
RTMS 61	24.33	5.99	69.79	5.99	32.92	5.99	19.47	3.84	10.24	3.84	NC*	-	NC*	-
RTMS 329	4.08	5.99	0.33	5.99	32.76	5.99	4.70	3.84	4.07	3.84	NC*	-	NC*	-
RTMS 316	12.04	11.07	38.63	11.07	71.69	12.59	16.93	14.07	15.88	11.07	43.32	9.49	NC*	-
RTMS 65	18.76	12.59	8.96	7.81	39.33	9.49	29.83	12.59	11.12	11.07	20.69	9.49	NC*	-
RTMS 317	9.07	11.07	37.92	11.07	42.42	11.07	40.35	12.59	23.32	11.07	0.34	3.84	NC*	-

*NC: no congestion

4.6.4 The effects of days of week on the speeds at congested flow area

K-W test results of the road speeds at the days of week at congested flow area are given in Table 4.15. The K-W tests of analyzed RTMSs show that:

- Daily speed data of 7 days are not coming from the same population. In other word, at least one day data are statistically different than the others.
- When 5 days speed data (Monday to Friday) are compared, it is not possible to conclude that they are statistically similar.
- Comparing speed data of 3 days (Tuesday to Thursday) shows that they are statistically similar at 40% of RTMSs.

- Saturday and Sunday speed data are statistically similar at only 20% of RTMSs.
- The comparison of speed data of successive days indicates that most similar days are Wednesday and Thursday according to speed at congested area. At 4 of analyzed 5 RTMSs, the speeds of these days are statistically similar. This similarity is observed at 60% of RTMSs between Thursday and Friday, Friday and Saturday speed data. At 40% of RTMSs Monday and Tuesday, Tuesday and Wednesday speed data are coming from the same population. Only at 20% of RTMSs Monday and Friday speed data are statistically similar.

Table 4.15 : K-W tests for days of week at congested area.

Test for	Days	RTMS 61		RTMS 329		RTMS 316		RTMS 65		RTMS 317	
		K	K _{crit.}	K	K _{crit.}	K	K _{crit.}	K	K _{crit.}	K	K _{crit.}
7 days	Monday to Sunday	22.31	11.07	31.04	12.59	19.19	11.07	33.51	11.07	28.57	11.07
5 days	Monday to Friday	15.54	9.49	23.98	9.49	17.84	9.49	31.62	9.49	26.82	9.49
3 days	Tuesday to Thursday	3.63	5.99	9.18	5.99	2.70	5.99	21.93	5.99	13.35	5.99
2 days	Saturday and Sunday	NC*	-	1.63	3.84	NC*	-	NC*	-	NC*	-
	Monday and Friday	8.62	3.84	7.14	3.84	13.42	3.84	8.00	3.84	2.78	3.84
	Monday and Tuesday	0.39	3.84	4.34	3.84	6.17	3.84	6.07	3.84	1.65	3.84
	Tuesday and Wednesday	0.76	3.84	8.77	3.84	2.43	3.84	5.47	3.84	13.00	3.84
	Wednesday and Thursday	1.52	3.84	0.38	3.84	0.05	3.84	20.94	3.84	1.95	3.84
	Thursday and Friday	1.49	3.84	7.15	3.84	0.13	3.84	4.55	3.84	3.40	3.84
	Friday and Saturday	11.08	3.84	7.27	3.84	0.00	3.84	0.66	3.84	3.02	3.84
	Sunday and Monday	NC*	-	4.56	3.84	NC*	-	NC*	-	NC*	-

*NC: no congestion

4.7 The Distribution of Free Flow Speed

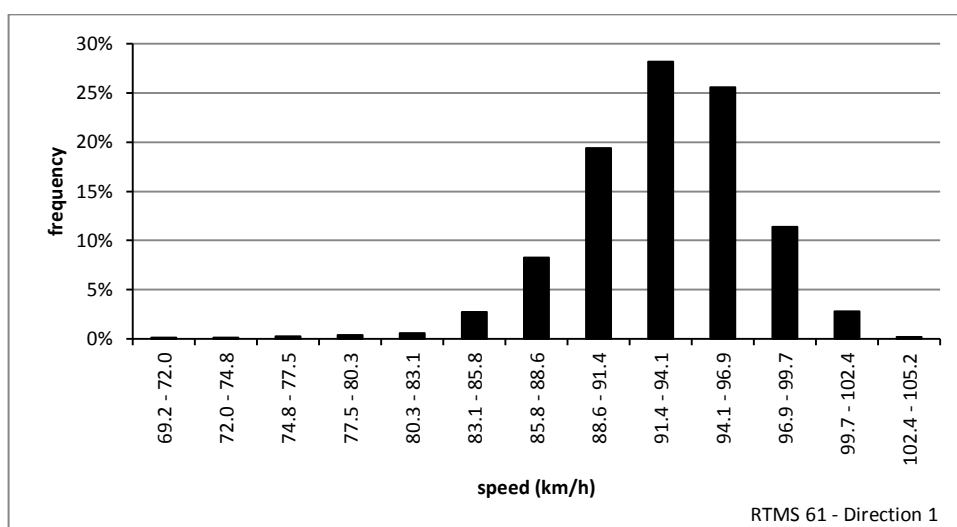
In this section, the distribution of free flow speed (FFS) is investigated by using Kolmogorov-Smirnov (K-S) test. Normal, lognormal, exponential, gamma, uniform, and gumbel distributions are tested in order to determine the distribution of FFS.

Initially, FFS data are extracted. The FFSs remain constant until a threshold value of flow rate. After this threshold flow rate, the FFS decreases when the flow rate increases, and the dropped speed can not be identified as FFS.

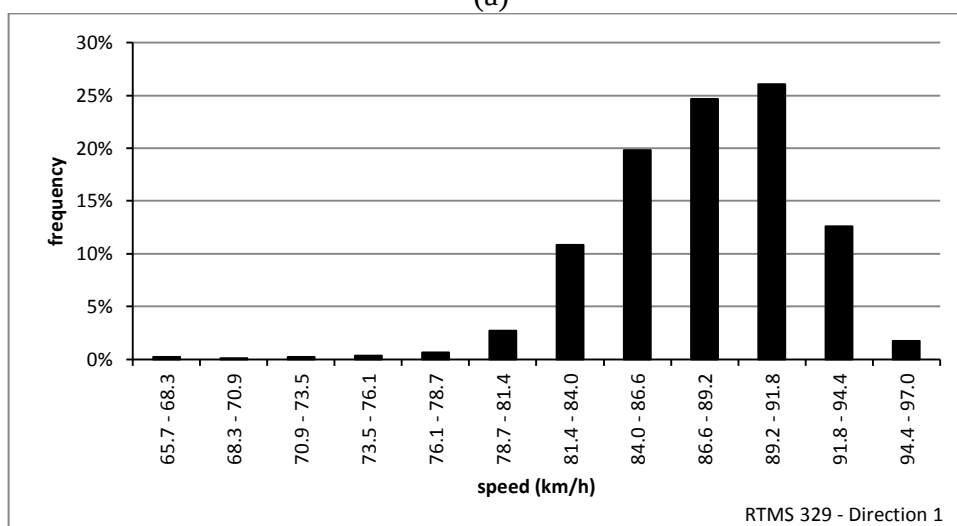
According to Tanış's research (2013), the maximum value of flow rate has been acquired as 1290 pc/h/l corresponding to 110 km/h FFS in Istanbul freeways [23]. On the analyzed RTMSs, the average long vehicle ratio is 0.26. Thus, the threshold value of flow rate is assumed as 1000 veh/h/l.

2-minute traffic data are assumed to move with FFS when flow rate is less than 1000 veh/h/l at uncongested area.

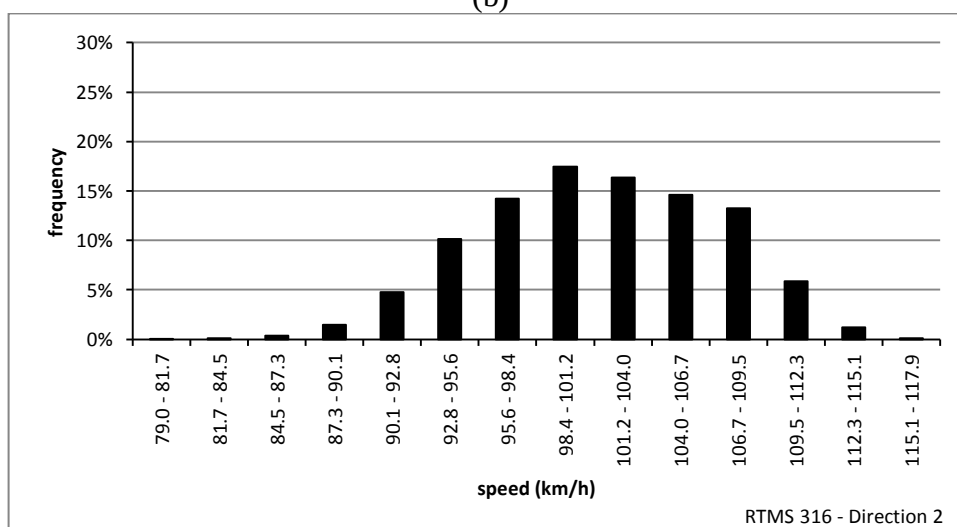
The histograms of FFS data are given in Figure 4.15 for 5 RTMSs.



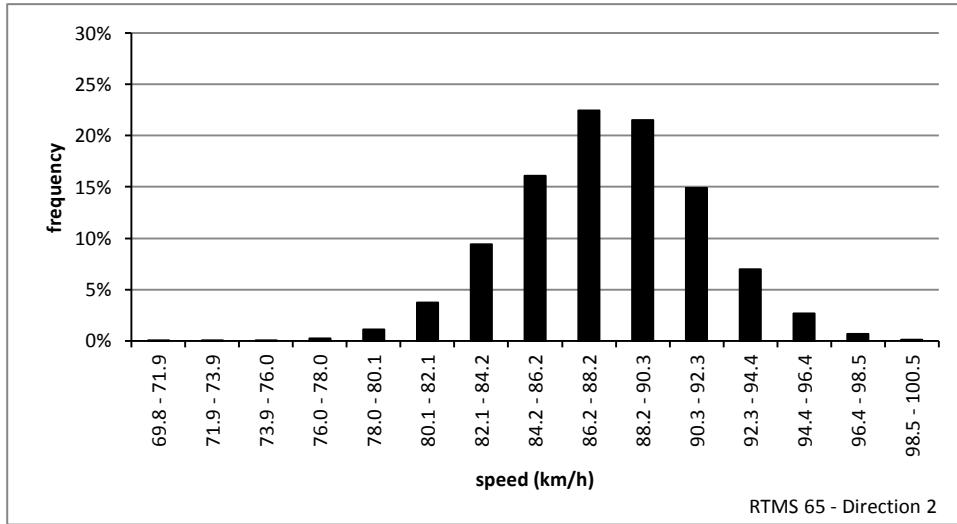
(a)



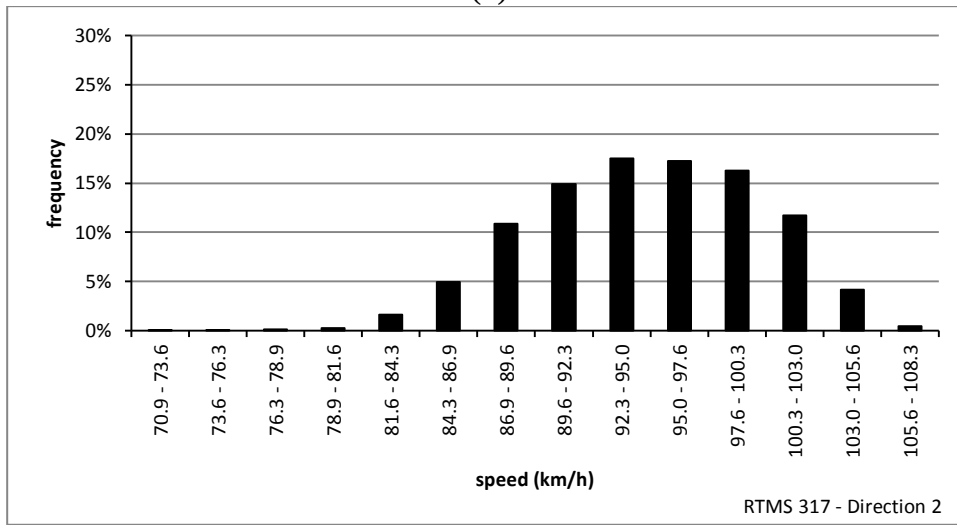
(b)



(c)



(d)



(e)

Figure 4.15 : Histograms of free flow speed data: (a)RTMS 61. (b)RTMS 329. (c)RTMS 316. (d)RTMS 65. (e)RTMS 317.

A large number of a random variable encountered in practical application fit to the normal (Gaussian) distribution with the following probability density function (pdf), as shown in Eq. (4.3), with two μ (the mean of the sample) and σ (the standard deviation of the sample) parameters, where $-\infty < \mu < +\infty$ and $\sigma > 0$ [24].

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (4.3)$$

Table 4.16 shows probability density functions of normal, lognormal, exponential, gamma, uniform, and gumbel distributions, respectively. In this table, σ is the standard deviation, μ represents the mean, σ^2 is the variance, and $\Gamma(\alpha)$ represents the gamma function evaluated at α . Table 4.17 indicates cumulative distribution

functions of normal, lognormal, exponential, gamma, uniform, and gumbel distributions, respectively. In this table, erf is the error function and γ represents the lower incomplete gamma function [24,25].

Table 4.16 : Probability density functions.

Distribution	Probability Density Function (pdf)	Parameters
Normal Distribution	$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, x \in (-\infty, +\infty)$	$\sigma \rightarrow scale \in (0, +\infty)$ $\mu \rightarrow location \in (-\infty, +\infty)$ $\sigma^2 \rightarrow squaredscale \in (0, +\infty)$
Lognormal Distribution	$f_X(x) = \frac{1}{x\sigma_{\ln(X)}\sqrt{2\pi}} e^{-\frac{(\ln x - \mu_{\ln(X)})^2}{2\sigma_{\ln(X)}^2}}, x \in (0, +\infty)$	$\sigma_{\ln(X)} \rightarrow shape \in (0, +\infty)$ $\mu_{\ln(X)} \rightarrow logscale \in (-\infty, +\infty)$ $\sigma_{\ln(X)}^2 \rightarrow squaredshape \in (0, +\infty)$
Exponential Distribution	$f(x) = \begin{cases} \lambda e^{-\lambda x}, & x \in [0, +\infty) \\ 0, & x \in (-\infty, 0) \end{cases}$	$\lambda \rightarrow rate/inversescale \in (0, +\infty)$ $\mu = \frac{1}{\lambda}$
Gamma Distribution	$f(x) = \begin{cases} \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}}, & x \in (0, +\infty) \\ 0, & x \in (-\infty, 0] \end{cases}$	$\alpha \rightarrow shape \in (0, +\infty)$ $\beta \rightarrow scale \in (0, +\infty)$ $\mu = \alpha\beta$ $\sigma^2 = \alpha\beta^2$
Uniform Distribution	$f(x) = \begin{cases} \frac{1}{b-a}, & x \in [a, b] \\ 0, & otherwise \end{cases}$	$a \rightarrow minimumvalue$ $b \rightarrow maximumvalue$ $-\infty < a < b < +\infty$
Gumbel Distribution	$f(x) = \alpha e^{-\alpha(x-\beta)-e^{-\alpha(x-\beta)}}, x \in (-\infty, +\infty)$	$\alpha \rightarrow rate \in (0, +\infty)$ $\beta \rightarrow location \in (-\infty, +\infty)$ $\sigma = \frac{\pi}{\alpha\sqrt{6}}$ $\mu = \beta + \frac{0.5772}{\alpha}$

In this study, K-S goodness-of-fit test is the test which is implemented to clarify whether a sample of a random variable fits to normal distribution or not. K-S test relates to the cumulative distribution function (cdf). Let $x_1, x_2, x_3, \dots, x_n$ represent a sample of size n , that is, the values arranged in increasing order. K-S test statistic (value of K-S) is the maximum absolute difference between the empirical (sample) and theoretical cdfs, which is determined by Eq. (4.4) [25].

Table 4.17 : Cumulative distribution functions.

Distribution	Cumulative Distribution Function (cdf)	Parameters
Normal Distribution	$F(x) = \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{x - \mu}{\sigma \sqrt{2}} \right) \right], x \in (-\infty, +\infty)$	$\mu \rightarrow \text{location} \in (-\infty, +\infty)$ $\sigma \rightarrow \text{scale} \in (0, +\infty)$
Lognormal Distribution	$F_X(x) = \frac{1}{2} + \frac{1}{2} \operatorname{erf} \left[\frac{\ln x - \mu_{\ln(X)}}{\sqrt{2} \sigma_{\ln(X)}} \right], x \in (0, +\infty)$	$\mu_{\ln(X)} \rightarrow \text{logscale} \in (-\infty, +\infty)$ $\sigma_{\ln(X)} \rightarrow \text{shape} \in (0, +\infty)$
Exponential Distribution	$F(x) = \begin{cases} 1 - e^{-\lambda x}, & x \in [0, +\infty) \\ 0, & x \in (-\infty, 0) \end{cases}$	$\lambda \rightarrow \text{rate/inversescale} \in (0, +\infty)$ $\mu = \frac{1}{\lambda}$
Gamma Distribution	$F(x) = \begin{cases} \frac{\gamma(\alpha, \frac{x}{\beta})}{\Gamma(\alpha)}, & x \in (0, +\infty) \\ 0, & x \in (-\infty, 0] \end{cases}$	$\alpha \rightarrow \text{shape} \in (0, +\infty)$ $\beta \rightarrow \text{scale} \in (0, +\infty)$ $\mu = \alpha\beta$ $\sigma^2 = \alpha\beta^2$
Uniform Distribution	$F(x) = \begin{cases} 0, & x \in (-\infty, a) \\ \frac{x-a}{b-a}, & x \in [a, b) \\ 1, & x \in [b, +\infty) \end{cases}$	$a \rightarrow \text{min imumvalue}$ $b \rightarrow \text{max imumvalue}$ $-\infty < a < b < +\infty$
Gumbel Distribution	$F(x) = e^{-e^{-\alpha(x-\beta)}}, x \in (-\infty, +\infty)$	$\alpha \rightarrow \text{rate} \in (0, +\infty)$ $\beta \rightarrow \text{location} \in (-\infty, +\infty)$ $\sigma = \frac{\pi}{\alpha \sqrt{6}}$ $\mu = \beta + \frac{0.5772}{\alpha}$

In this equation, $F^*(x_i) = i/n$ ($i=1, 2, 3, \dots, n$) are the cumulative frequencies of the observed data x_i , and $F(x_i)$ are the cumulative probabilities corresponding to x_i of the normal distribution function (Eq. (4.3)). Therefore, the K-S statistic is the positive value of the largest difference between the two cumulative probabilities. Here, the empirical or sample distribution function $F^*(x_i)$ is a step function and the theoretical distribution function $F(x_i)$ is a continuous function [25].

In this process, null hypothesis H_0 is when the random variable fit to normal distribution and alternate hypothesis H_1 is when the random variable does not fit to normal distribution [25].

In this study, for all of the samples, the critical value for K-S, $(K-S)_{\text{critical}}$, is calculated by $1.3581/\sqrt{n}$ for level of significance $\alpha = 0.05$. For a sample, when the computed K-S test statistic is bigger than the critical value of K-S test, $(K-S)_{\text{critical}}$, then null hypothesis H_0 is rejected and the sample does not fit to normal distribution. On the other hand, for a sample, when the computed K-S test statistic is smaller than the critical value of K-S test, then null hypothesis H_0 is accepted and the sample fits to normal distribution [25].

$$K - S = \max_i |F^*(x_i) - F(x_i)| \quad (4.4)$$

In subsequent step, it is investigated that either the distribution of FFS is normal or not. K-S tests were implemented at 5% level of significance to FFS data for each lane and road section of each RTMS on each day of week. The results of these tests are shown in Table 4.18 for normal distribution.

K-S tests are made to the same data sets for lognormal, exponential, gamma, uniform and gumbel distributions. The results of these tests are given in Table 4.18 – 4.20 and Table A.1 – A.3 for each distribution separately.

Table 4.18 – 4.20 show the results of K-S tests for normal, lognormal and gamma distributions, respectively. In Appendix B, Table A.1 – A.3 show these results for gumbel, exponential and uniform distributions, respectively.

For each distribution 175 (5 RTMSs $\times$ 5 lanes (4 lanes + 1 road in general) $\times$ 7 days = 175) K-S tests are implemented. It is indicated that at these 175 tests (each test indicate a defined RTMS, lane and day of week) the FFS data fit to:

- Normal distribution 34 times (19%)
- Lognormal distribution 31 times (18%)
- Exponential distribution 0 times (0%)
- Gamma distribution 33 times (19%)
- Uniform distribution 0 times (0%)
- Gumbel distribution 5 times (3%)

The RTMS – Lane – day of week data that fits to corresponding distribution is marked with dark texture in related tables.

Table 4.18 : K-S tests for normal distribution at free speed region.

Direction	RTMS No.	Lane No.	Mondays		Tuesdays		Wednesdays		Thursdays		Fridays		Saturdays		Sundays	
			K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}
Direction 1	RTMS 61	Lane 1	0.11	0.04	0.13	0.04	0.13	0.04	0.11	0.04	0.13	0.04	0.06	0.04	0.07	0.03
		Lane 2	0.10	0.04	0.10	0.05	0.11	0.04	0.10	0.05	0.11	0.05	0.09	0.05	0.06	0.04
		Lane 3	0.07	0.06	0.060	0.056	0.07	0.05	0.05	0.07	0.074	0.069	0.06	0.07	0.09	0.05
		Lane 4	0.11	0.05	0.09	0.05	0.12	0.05	0.07	0.06	0.09	0.06	0.08	0.06	0.14	0.05
		Road Section	0.04	0.05	0.06	0.05	0.05	0.04	0.06	0.05	0.03	0.06	0.03	0.05	0.06	0.04
	RTMS 329	Lane 1	0.06	0.05	0.06	0.09	0.04	0.07	0.060	0.057	0.064	0.058	0.07	0.05	0.08	0.04
		Lane 2	0.0582	0.0579	0.05	0.10	0.05	0.07	0.06	0.07	0.08	0.07	0.05	0.06	0.08	0.04
		Lane 3	0.09	0.08	0.09	0.13	0.06	0.08	0.06	0.09	0.14	0.10	0.10	0.12	0.08	0.06
		Lane 4	0.14	0.07	0.16	0.10	0.16	0.08	0.16	0.08	0.13	0.08	0.14	0.09	0.15	0.05
		Road Section	0.05	0.06	0.05	0.10	0.05	0.07	0.04	0.07	0.05	0.07	0.04	0.07	0.036	0.045
Direction 2	RTMS 316	Lane 1	0.04	0.02	0.04	0.02	0.04	0.02	0.07	0.03	0.06	0.02	0.05	0.02	0.06	0.02
		Lane 2	0.08	0.03	0.07	0.04	0.036	0.040	0.06	0.04	0.05	0.04	0.05	0.03	0.06	0.03
		Lane 3	0.09	0.05	0.061	0.059	0.08	0.06	0.09	0.06	0.07	0.05	0.06	0.04	0.08	0.03
		Lane 4	0.08	0.04	0.09	0.06	0.09	0.06	0.10	0.06	0.09	0.05	0.09	0.04	0.12	0.03
		Road Section	0.08	0.04	0.03	0.05	0.045	0.044	0.09	0.05	0.07	0.04	0.04	0.03	0.031	0.027
	RTMS 65	Lane 1	0.06	0.02	0.07	0.02	0.06	0.02	0.06	0.02	0.08	0.02	0.06	0.02	0.07	0.02
		Lane 2	0.04	0.03	0.07	0.03	0.08	0.03	0.09	0.03	0.08	0.03	0.07	0.03	0.05	0.03
		Lane 3	0.08	0.04	0.06	0.04	0.07	0.04	0.09	0.04	0.07	0.03	0.08	0.04	0.08	0.03
		Lane 4	0.07	0.03	0.06	0.03	0.07	0.03	0.08	0.03	0.05	0.03	0.08	0.03	0.07	0.03
		Road Section	0.02	0.03	0.01	0.03	0.02	0.03	0.027	0.033	0.02	0.03	0.02	0.03	0.01	0.03
	RTMS 317	Lane 1	0.05	0.03	0.06	0.03	0.07	0.03	0.10	0.03	0.08	0.03	0.06	0.02	0.05	0.02
		Lane 2	0.08	0.03	0.03	0.04	0.04	0.03	0.07	0.04	0.06	0.03	0.04	0.03	0.07	0.02
		Lane 3	0.13	0.04	0.09	0.05	0.08	0.04	0.07	0.05	0.09	0.04	0.11	0.04	0.10	0.03
		Lane 4	0.09	0.04	0.08	0.04	0.10	0.04	0.10	0.05	0.10	0.04	0.09	0.03	0.09	0.03
		Road Section	0.08	0.03	0.03	0.04	0.03	0.04	0.09	0.04	0.07	0.04	0.030	0.029	0.04	0.03

Table 4.19 : K-S tests for lognormal distribution at free speed region.

Direction	RTMS No.	Lane No.	Mondays		Tuesdays		Wednesdays		Thursdays		Fridays		Saturdays		Sundays	
			K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}
Direction 1	RTMS 61	Lane 1	0.13	0.04	0.15	0.04	0.14	0.04	0.12	0.04	0.15	0.04	0.07	0.04	0.08	0.03
		Lane 2	0.11	0.04	0.12	0.05	0.12	0.04	0.11	0.05	0.12	0.05	0.10	0.05	0.06	0.04
		Lane 3	0.07	0.06	0.07	0.06	0.09	0.05	0.06	0.07	0.09	0.07	0.06	0.07	0.10	0.05
		Lane 4	0.12	0.05	0.10	0.05	0.13	0.05	0.07	0.06	0.09	0.06	0.09	0.06	0.14	0.05
		Road Section	0.054	0.046	0.07	0.05	0.06	0.04	0.06	0.05	0.04	0.06	0.04	0.05	0.07	0.04
	RTMS 329	Lane 1	0.08	0.05	0.08	0.09	0.05	0.07	0.056	0.057	0.08	0.06	0.08	0.05	0.09	0.04
		Lane 2	0.07	0.06	0.06	0.10	0.06	0.07	0.0684	0.0680	0.10	0.07	0.060	0.063	0.09	0.04
		Lane 3	0.10	0.08	0.09	0.13	0.07	0.08	0.06	0.09	0.15	0.10	0.09	0.12	0.09	0.06
		Lane 4	0.15	0.07	0.17	0.10	0.16	0.08	0.16	0.08	0.14	0.08	0.15	0.09	0.15	0.05
Direction 2	RTMS 316	Road Section	0.063	0.061	0.05	0.10	0.05	0.07	0.04	0.07	0.06	0.07	0.05	0.07	0.042	0.045
		Lane 1	0.04	0.02	0.04	0.02	0.05	0.02	0.07	0.03	0.07	0.02	0.06	0.02	0.07	0.02
		Lane 2	0.10	0.03	0.09	0.04	0.041	0.040	0.043	0.045	0.05	0.04	0.06	0.03	0.07	0.03
		Lane 3	0.10	0.05	0.064	0.059	0.09	0.06	0.08	0.06	0.07	0.05	0.07	0.04	0.09	0.03
		Lane 4	0.09	0.04	0.09	0.06	0.09	0.06	0.10	0.06	0.09	0.05	0.10	0.04	0.12	0.03
	RTMS 65	Road Section	0.09	0.04	0.03	0.05	0.03	0.04	0.08	0.05	0.07	0.04	0.034	0.032	0.035	0.027
		Lane 1	0.07	0.02	0.07	0.02	0.07	0.02	0.07	0.02	0.07	0.02	0.06	0.02	0.06	0.02
		Lane 2	0.05	0.03	0.08	0.03	0.10	0.03	0.11	0.03	0.09	0.03	0.07	0.03	0.04	0.03
		Lane 3	0.07	0.04	0.07	0.04	0.07	0.04	0.08	0.04	0.07	0.03	0.07	0.04	0.07	0.03
		Lane 4	0.08	0.03	0.06	0.03	0.07	0.03	0.07	0.03	0.07	0.03	0.06	0.03	0.08	0.03
	RTMS 317	Road Section	0.02	0.03	0.02	0.03	0.027	0.030	0.035	0.033	0.030	0.031	0.027	0.029	0.01	0.03
		Lane 1	0.04	0.03	0.05	0.03	0.05	0.03	0.08	0.03	0.07	0.03	0.06	0.02	0.06	0.02
		Lane 2	0.10	0.03	0.05	0.04	0.04	0.03	0.05	0.04	0.04	0.03	0.04	0.03	0.08	0.02
		Lane 3	0.14	0.04	0.10	0.05	0.09	0.04	0.08	0.05	0.11	0.04	0.12	0.04	0.11	0.03
		Lane 4	0.10	0.04	0.09	0.04	0.10	0.04	0.10	0.05	0.10	0.04	0.10	0.03	0.09	0.03
		Road Section	0.08	0.03	0.037	0.041	0.02	0.04	0.08	0.04	0.06	0.04	0.033	0.029	0.04	0.03

Table 4.20 : K-S tests for gamma distribution at free speed region.

Direction	RTMS No.	Lane No.	Mondays		Tuesdays		Wednesdays		Thursdays		Fridays		Saturdays		Sundays	
			K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}
Direction 1	RTMS 61	Lane 1	0.12	0.04	0.14	0.04	0.14	0.04	0.12	0.04	0.14	0.04	0.07	0.04	0.07	0.03
		Lane 2	0.10	0.04	0.11	0.05	0.11	0.04	0.10	0.05	0.12	0.05	0.10	0.05	0.06	0.04
		Lane 3	0.064	0.060	0.065	0.056	0.08	0.05	0.05	0.07	0.08	0.07	0.06	0.07	0.09	0.05
		Lane 4	0.11	0.05	0.09	0.05	0.13	0.05	0.07	0.06	0.09	0.06	0.09	0.06	0.14	0.05
		Road Section	0.048	0.046	0.07	0.05	0.05	0.04	0.06	0.05	0.03	0.06	0.04	0.05	0.06	0.04
	RTMS 329	Lane 1	0.07	0.05	0.07	0.09	0.05	0.07	0.05	0.06	0.07	0.06	0.08	0.05	0.08	0.04
		Lane 2	0.060	0.058	0.05	0.10	0.06	0.07	0.06	0.07	0.08	0.07	0.056	0.063	0.09	0.04
		Lane 3	0.09	0.08	0.08	0.13	0.07	0.08	0.06	0.09	0.14	0.10	0.09	0.12	0.08	0.06
		Lane 4	0.15	0.07	0.16	0.10	0.15	0.08	0.16	0.08	0.13	0.08	0.14	0.09	0.15	0.05
Direction 2	RTMS 316	Road Section	0.05	0.06	0.05	0.10	0.05	0.07	0.04	0.07	0.05	0.07	0.04	0.07	0.036	0.045
		Lane 1	0.04	0.02	0.03	0.02	0.05	0.02	0.07	0.03	0.07	0.02	0.06	0.02	0.07	0.02
		Lane 2	0.09	0.03	0.08	0.04	0.03	0.04	0.05	0.04	0.05	0.04	0.05	0.03	0.06	0.03
		Lane 3	0.09	0.05	0.063	0.059	0.08	0.06	0.09	0.06	0.07	0.05	0.07	0.04	0.08	0.03
	RTMS 65	Lane 4	0.09	0.04	0.09	0.06	0.09	0.06	0.10	0.06	0.09	0.05	0.10	0.04	0.12	0.03
		Road Section	0.09	0.04	0.03	0.05	0.038	0.044	0.08	0.05	0.07	0.04	0.034	0.032	0.034	0.027
		Lane 1	0.06	0.02	0.07	0.02	0.07	0.02	0.07	0.02	0.07	0.02	0.06	0.02	0.06	0.02
		Lane 2	0.04	0.03	0.08	0.03	0.09	0.03	0.10	0.03	0.09	0.03	0.07	0.03	0.05	0.03
	RTMS 317	Lane 3	0.07	0.04	0.07	0.04	0.06	0.04	0.08	0.04	0.07	0.03	0.07	0.04	0.07	0.03
		Lane 4	0.08	0.03	0.05	0.03	0.07	0.03	0.07	0.03	0.06	0.03	0.07	0.03	0.08	0.03
		Road Section	0.02	0.03	0.01	0.03	0.02	0.03	0.031	0.033	0.026	0.031	0.02	0.03	0.01	0.03
		Lane 1	0.04	0.03	0.05	0.03	0.05	0.03	0.08	0.03	0.07	0.03	0.06	0.02	0.06	0.02
	RTMS 317	Lane 2	0.09	0.03	0.05	0.04	0.04	0.03	0.06	0.04	0.05	0.03	0.05	0.03	0.08	0.02
		Lane 3	0.13	0.04	0.10	0.05	0.09	0.04	0.08	0.05	0.10	0.04	0.11	0.04	0.11	0.03
		Lane 4	0.09	0.04	0.08	0.04	0.10	0.04	0.10	0.05	0.10	0.04	0.10	0.03	0.09	0.03
		Road Section	0.08	0.03	0.035	0.041	0.02	0.04	0.08	0.04	0.06	0.04	0.032	0.029	0.04	0.03

4.8 Road Speed – Maximum Speed Difference across Lanes Relations

In this section, it is analyzed that either the maximum speed differences across lanes are related with road speed or not. The road speed – maximum speed difference across lanes relations for uncongested and congested flow areas are performed separately.

4.8.1 Road speed – maximum speed difference across lanes relations for uncongested area

The maximum speed differences across lanes are calculated for each RTMS and all study days. Here, maximum speed difference between four lanes for each 2-minute speed data is considered. By using the maximum speed difference data of uncongested area and the whole study days road speed data (in 2-minute intervals) of the same area for each RTMS, road speed – maximum speed difference across lanes diagrams were drawn for all RTMSs as shown in Figure 4.16 and Figure 4.17 for Direction 1 and Direction 2, respectively.

As shown in these figures, regression analysis was implemented for road speed – maximum speed difference across lanes diagram of each RTMS.

We see in various engineering problems that the values of two (or more) random variables take in an observation are not statistically independent of each other, thus there is a relation between these variables. The existence of such a relation show either that that one variable is affected by the other or that both variables are affected by other variables. The mathematical expression showing a relation of the above mentioned type is called the regression equation or model. The aim of the regression analysis is to check whether there is a significant relation between the variables under consideration and, if there is one, then to obtain the regression equation expressing this relation and to evaluate the confidence interval of the future assessments and estimates to be made by using this equation [26].

The correlation coefficient (R) is a numerical measure of the strength and direction of the linear association between two random variables. This quantity is dimensionless and is between -1 for perfect negative correlation and $+1$ for perfect positive correlation. Positive values of the correlation coefficient mean that greater values of one variable are associated with greater values of the other. Negative

values of the correlation coefficient indicate that greater values of one variable are associated with lesser values of the other. Correlation coefficient being zero shows that there is no linear dependence between two variables. Values of the correlation coefficient close to 1 or to -1 indicate a strong linear relationship; values close to 0 indicate a weak linear relationship between two variables. The value of the correlation coefficient helps to decide whether there is a significant relationship between the two random variables [26].

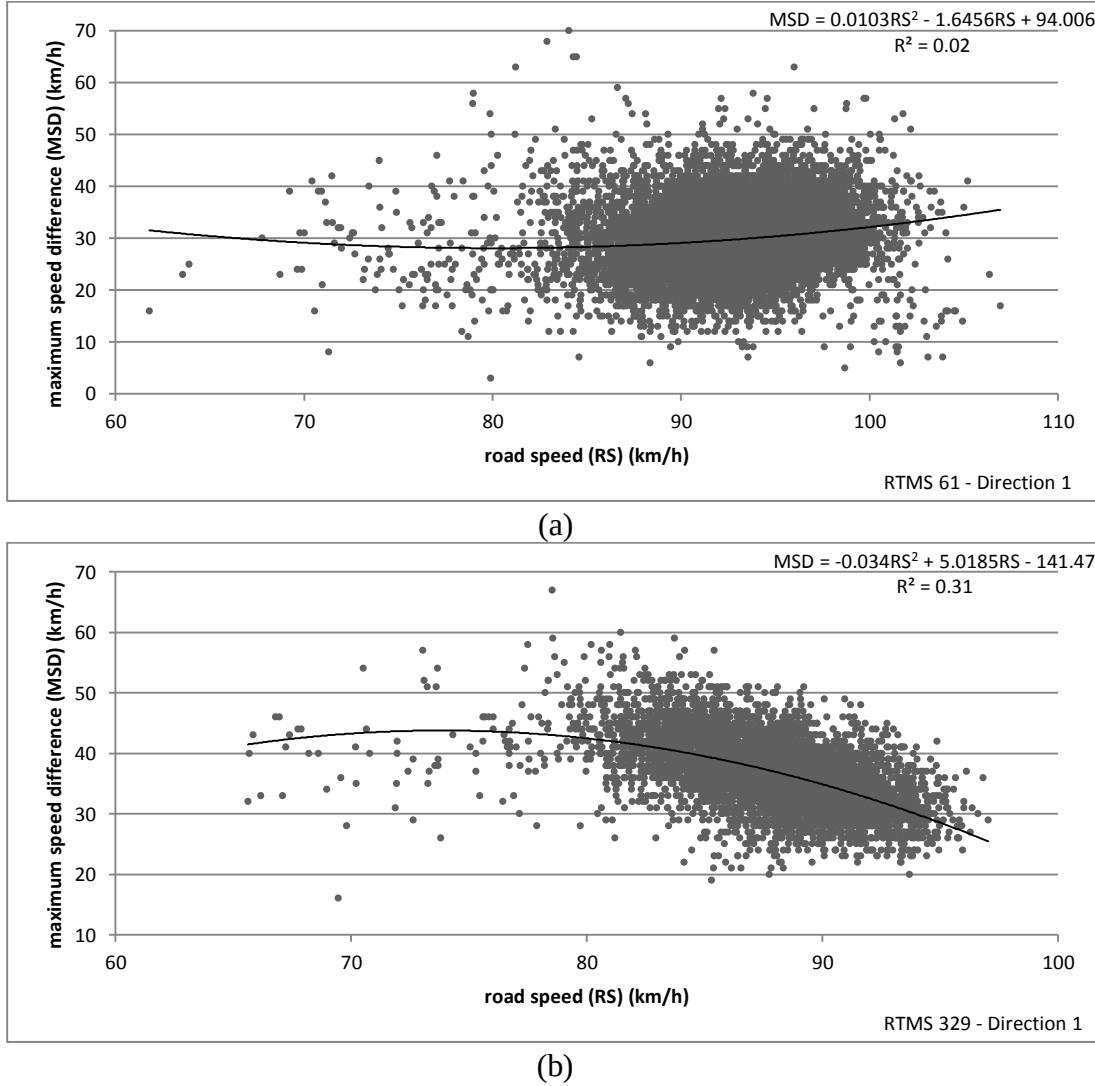
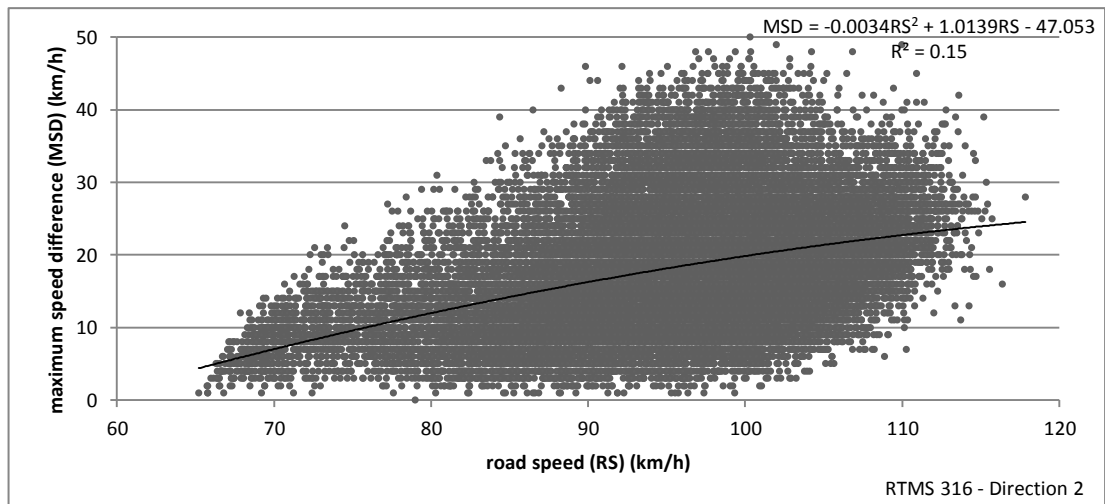
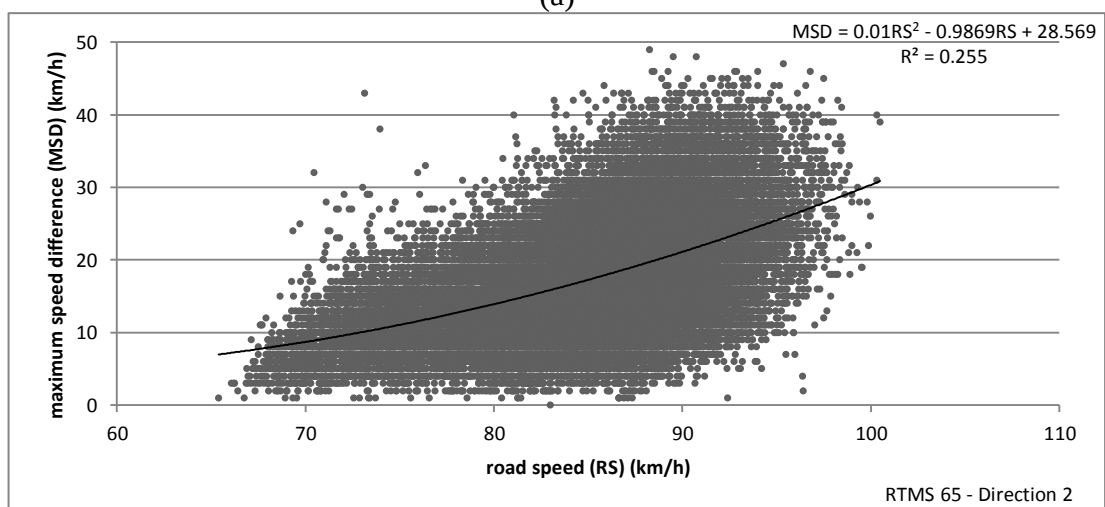


Figure 4.16 : Road speed – maximum speed difference across lanes diagrams of Direction 1 for uncongested area: (a)RTMS 61. (b)RTMS 329.

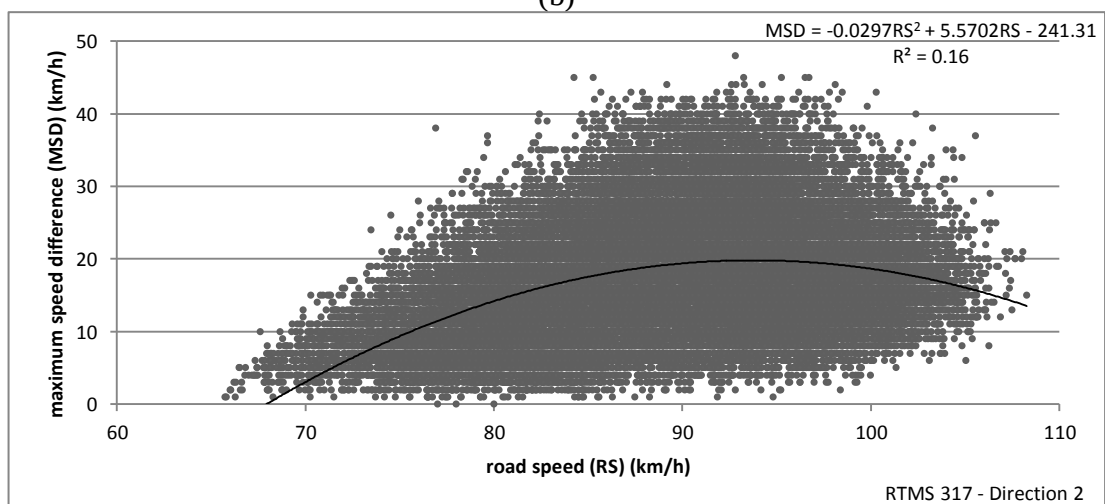
The coefficient of determination (R^2) is often used to judge the adequacy of a regression model. In other words, R-squared is a statistical measure of how well a regression model approximates/predicts observed real data. This quantity is the square of the correlation coefficient (R). R^2 is a descriptive measure between zero and one. The higher value of R^2 shows the more successful regression model [25].



(a)



(b)



(c)

Figure 4.17 : Road speed – maximum speed difference across lanes diagrams of Direction 2 for uncongested area: (a)RTMS 316. (b)RTMS 65. (c)RTMS 317.

R^2 gives the proportion (or fraction) of the variability of the response (dependent) variable that is accounted by the explanatory (independent) variables [25].

The regression equation and the coefficient of determination (R^2) were obtained by considering and utilizing linear, exponential, logarithmic, 2^o polynomial, and power functions. And, the function with highest R^2 value was selected as the regression equation of each RTMS.

It can be concluded from these equations and their related R^2 values that there are two medium values of R^2 and thus medium values of correlation coefficient (R). In Direction 1, this R^2 value is 0.31 belongs to RTMS 329. In Direction 2, this R^2 values is 0.255 belongs to RTMS 65. Therefore, it is derived that there is moderate relationship between maximum speed difference across lanes and road speed for each of above mentioned RTMSs. Related R^2 values of other RTMSs and equations indicate weak relationship between maximum speed difference across lanes and road speed.

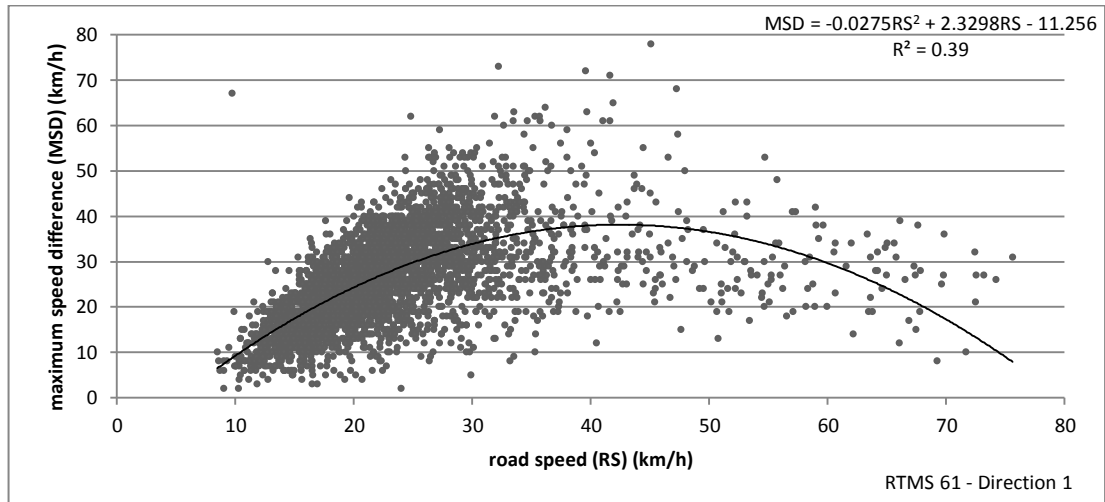
4.8.2 Road speed – maximum speed difference across lanes relations for congested area

The maximum speed differences across lanes are calculated for each RTMS and all study days. Here, maximum speed difference between four lanes for each 2-minute speed data is considered. By using the maximum speed difference data of congested area and the whole study days road speed data (in 2-minute intervals) of the same area for each RTMS, road speed – maximum speed difference across lanes diagrams were drawn for all RTMSs as shown in Figure 4.18 and Figure 4.19 for Direction 1 and Direction 2, respectively.

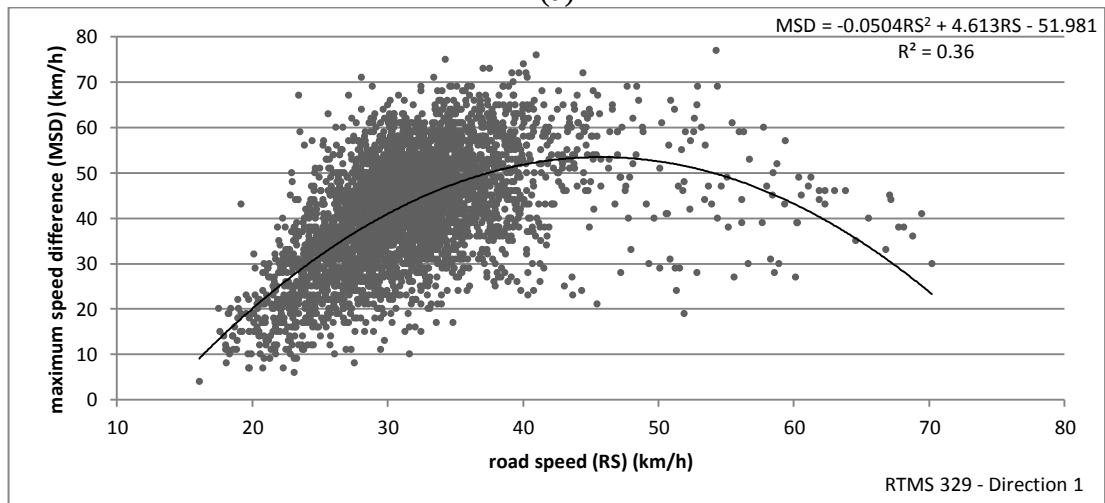
As shown in these figures, regression analysis was implemented for road speed – maximum speed difference across lanes diagram of each RTMS. The regression equation and the coefficient of determination (R^2) were obtained by considering and utilizing linear, exponential, logarithmic, 2^o polynomial, and power functions. And, the function with highest R^2 value was selected as the regression equation of each RTMS.

It can be concluded from these equations and their related R^2 values that there are three medium values of R^2 and thus medium values of correlation coefficient (R). In

Direction 1, these R^2 values are 0.39 and 0.36 belong to RTMS 61 and RTMS 329, respectively. In Direction 2, this R^2 values is 0.36 belongs to RTMS 65. Therefore, it is derived that there is moderate relationship between maximum speed difference across lanes and road speed for each of above mentioned RTMSs. Related R^2 values of other RTMSs and equations indicate weak relationship between maximum speed difference across lanes and road speed.

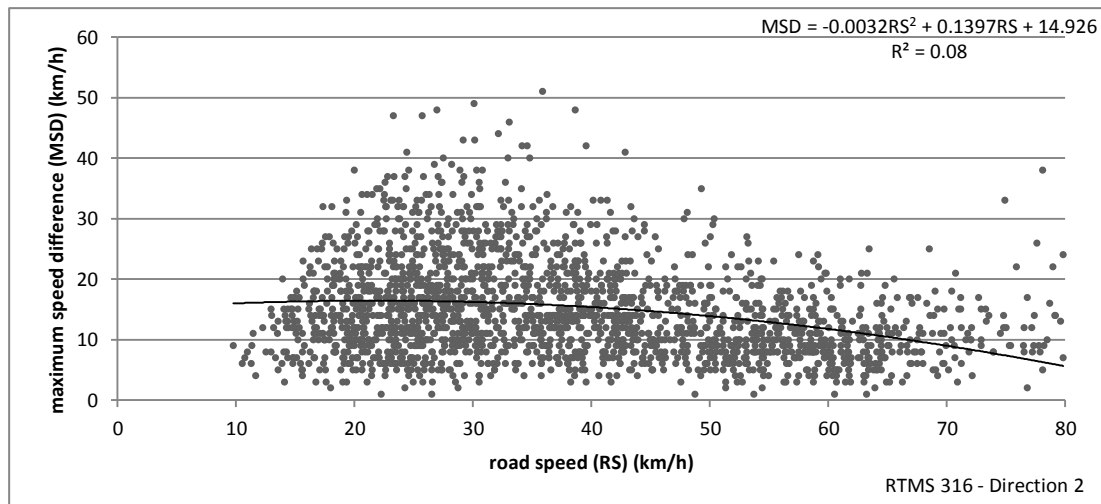


(a)

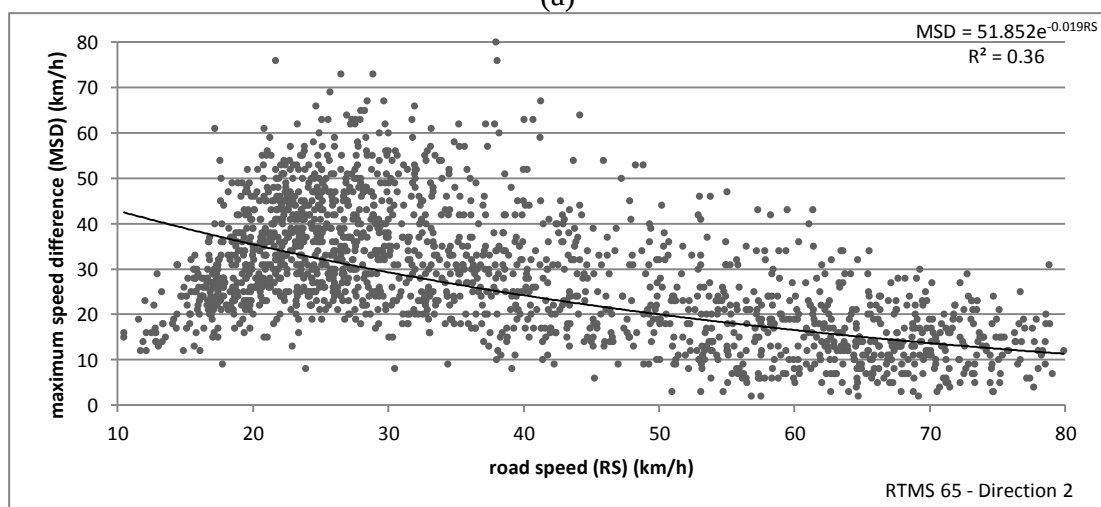


(b)

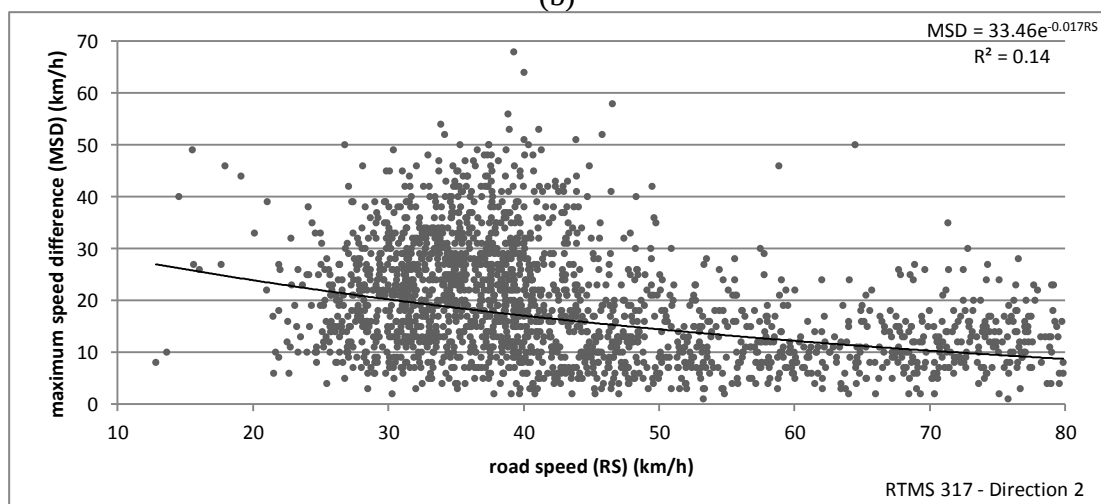
Figure 4.18 : Road speed – maximum speed difference across lanes diagrams of Direction 1 for congested area: (a)RTMS 61. (b)RTMS 329.



(a)



(b)



(c)

Figure 4.19 : Road speed – maximum speed difference across lanes diagrams of Direction 2 for congested area: (a)RTMS 316. (b)RTMS 65. (c)RTMS 317.

4.9 Road Flow Rate – Maximum Speed Difference across Lanes Relations

In this section, the road flow rate – maximum speed difference across lanes relations for uncongested and congested flow areas are performed, separately. Here, it is analyzed that either the maximum speed differences across lanes are related with road flow rate or not.

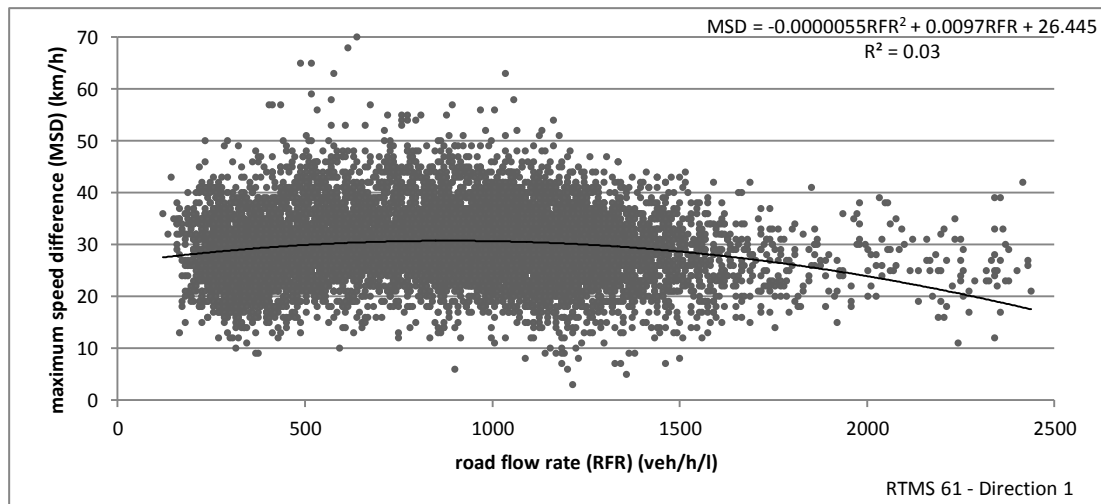
4.9.1 Road flow rate – maximum speed difference across lanes relations for uncongested area

The maximum speed differences across lanes are calculated for each RTMS and all study days. Here, maximum speed difference between four lanes for each 2-minute speed data is considered. By using the maximum speed difference data of uncongested area and the whole study days road flow rate data (based on 2-minute intervals) of the same area for each RTMS, road flow rate – maximum speed difference across lanes diagrams were drawn for all RTMSs as shown in Figure 4.20 and Figure 4.21 for Direction 1 and Direction 2, respectively.

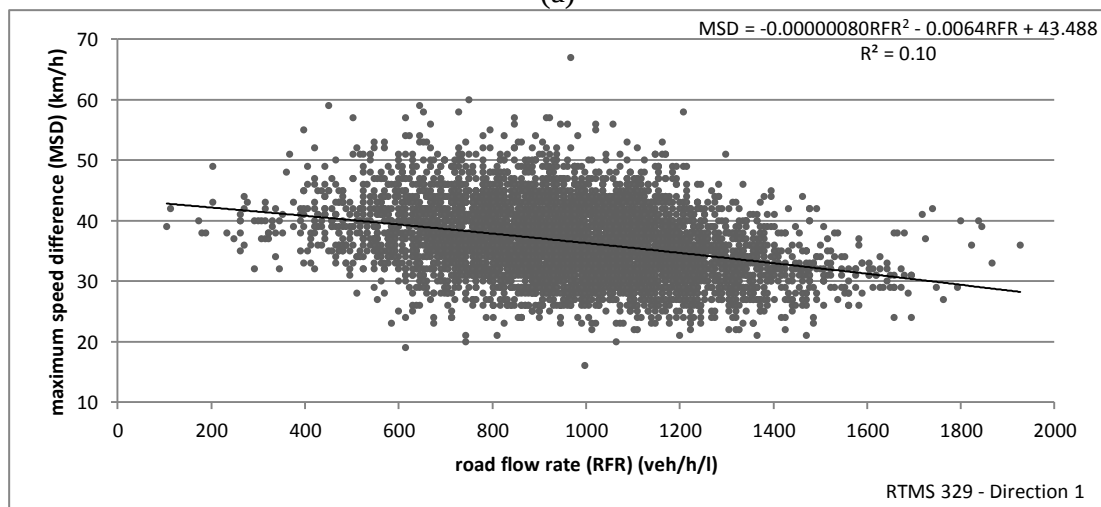
As shown in these figures, regression analysis was implemented for road flow rate – maximum speed difference across lanes diagram of each RTMS.

The regression equation and the coefficient of determination (R^2) were obtained by considering and utilizing linear, exponential, logarithmic, 2^o polynomial, and power functions. And, the function with highest R^2 value was selected as the regression equation of each RTMS.

It can be concluded from these equations and their related R^2 values that there are two medium values of R^2 and thus medium values of correlation coefficient (R). These R^2 values are 0.43 and 0.44 belong to RTMS 316 and RTMS 317 in Direction 2, respectively. Therefore, it is derived that there is moderate relationship between maximum speed difference across lanes and road flow rate for each of above mentioned RTMSs. The maximum speed difference across lanes decreases as the road flow rate increases; similarly, the maximum speed difference across lanes increases when the road flow rate decreases. Related R^2 values of other RTMSs and equations indicate weak relationship between maximum speed difference across lanes and road flow rate.

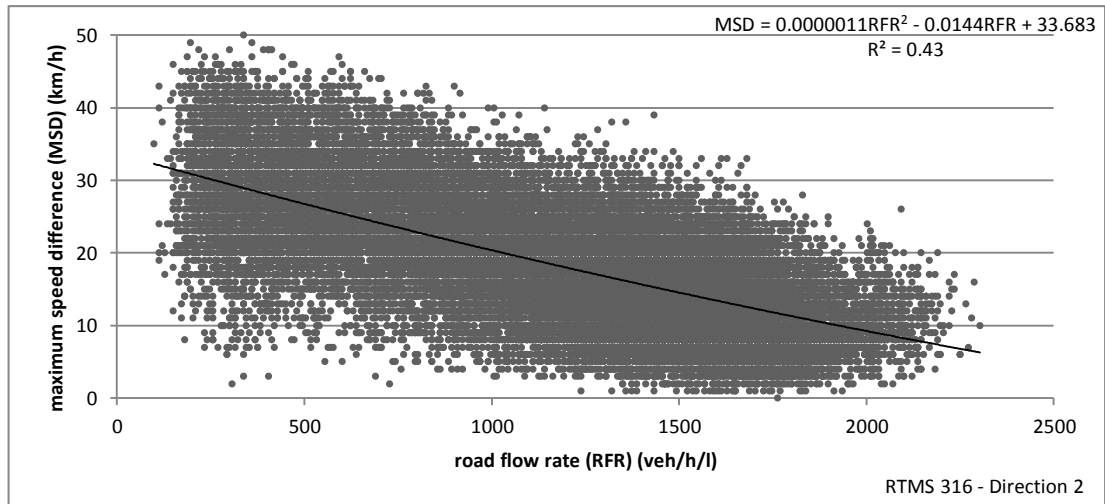


(a)

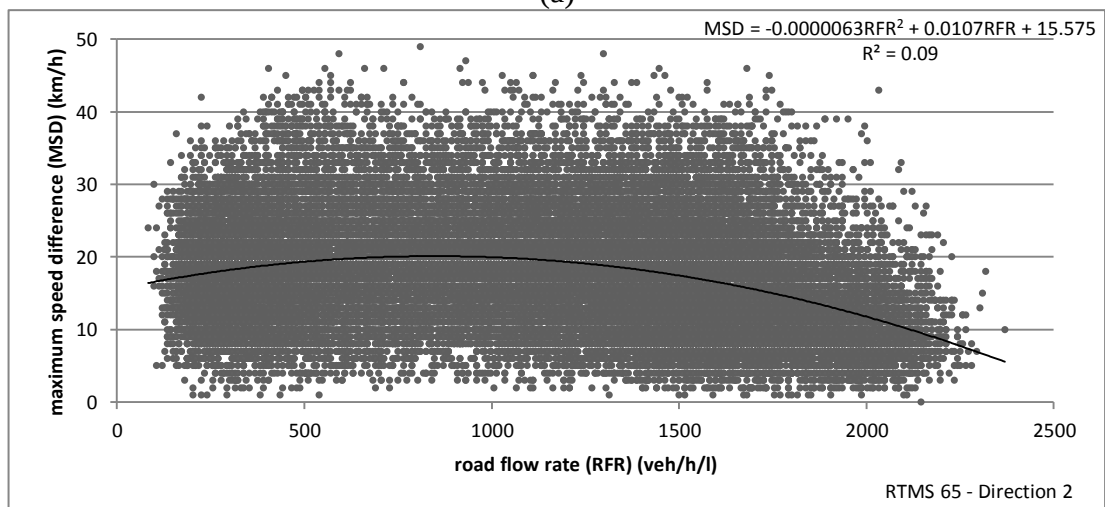


(b)

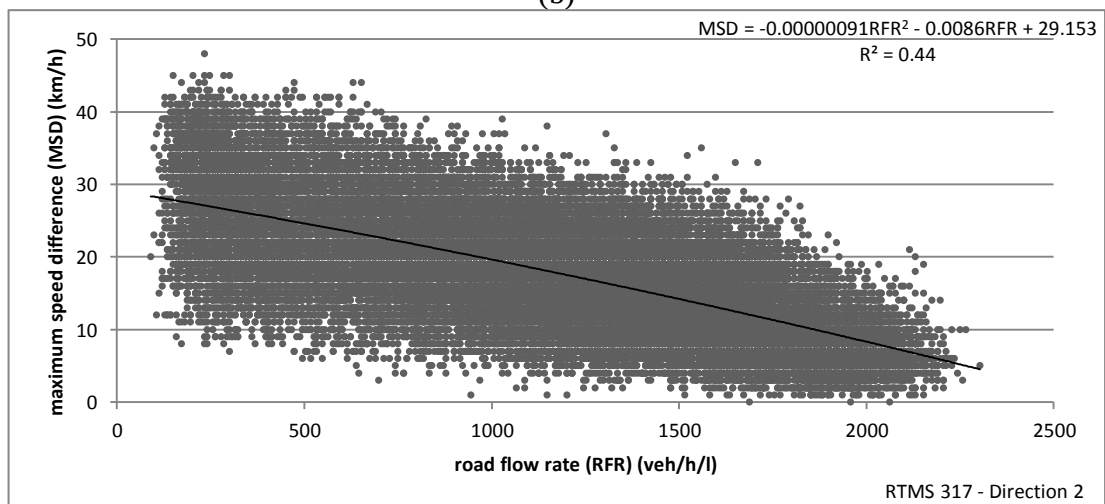
Figure 4.20 : Road flow rate – maximum speed difference across lanes diagrams of Direction 1 for uncongested area: (a)RTMS 61. (b)RTMS 329.



(a)



(b)



(c)

Figure 4.21 : Road flow rate – maximum speed difference across lanes diagrams of Direction 2 for uncongested area: (a)RTMS 316. (b)RTMS 65. (c)RTMS 317.

4.9.2 Road flow rate – maximum speed difference across lanes relations for congested area

The maximum speed differences across lanes are calculated for each RTMS and all study days. Here, maximum speed difference between four lanes for each 2-minute speed data is considered. By using the maximum speed difference data of congested area and the whole study days road flow rate data (based on 2-minute intervals) of the same area for each RTMS, road flow rate – maximum speed difference across lanes diagrams were drawn for all RTMSs as shown in Figure 4.22 and Figure 4.23 for Direction 1 and Direction 2, respectively.

As shown in these figures, regression analysis was implemented for road flow rate – maximum speed difference across lanes diagram of each RTMS.

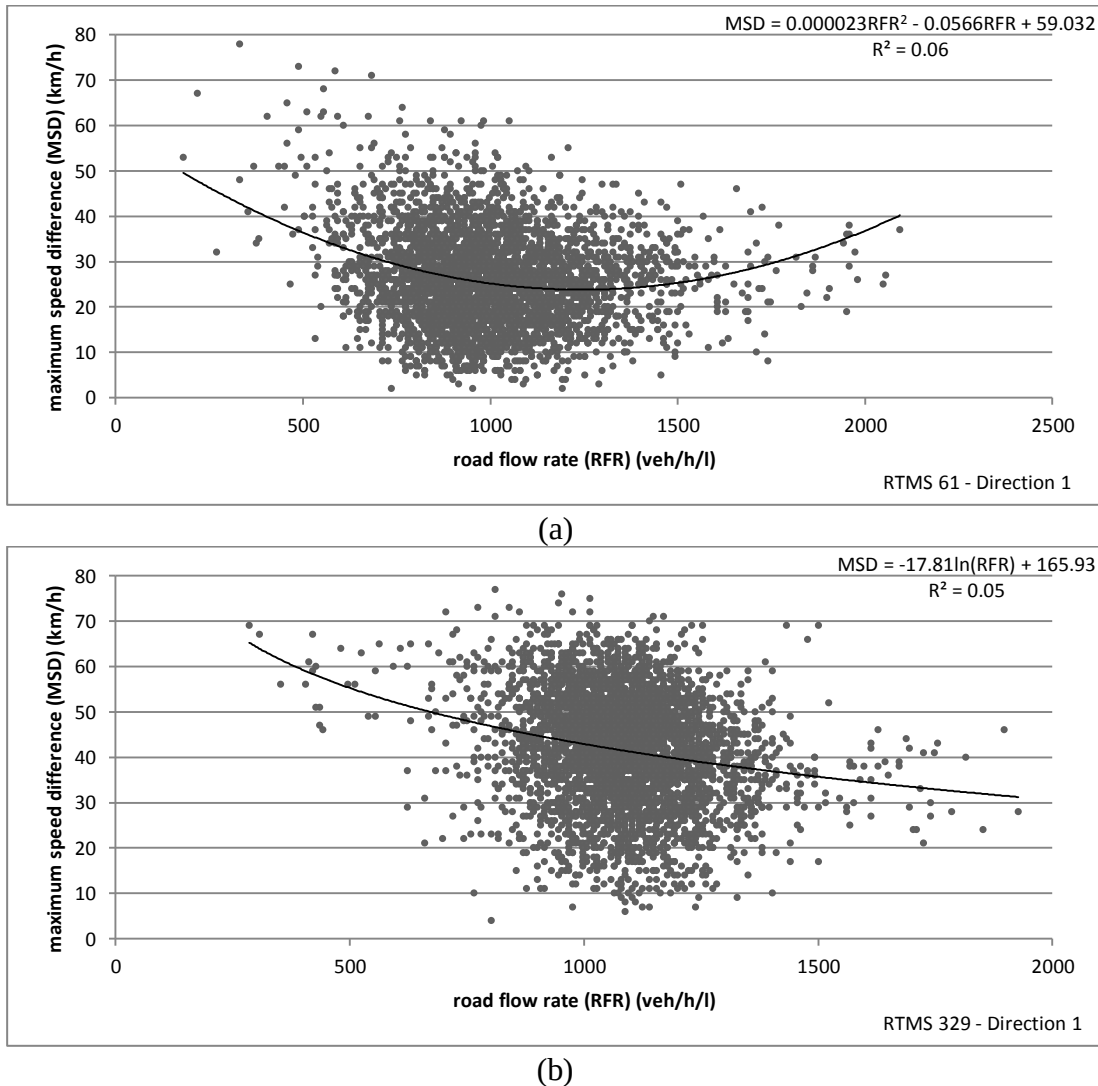
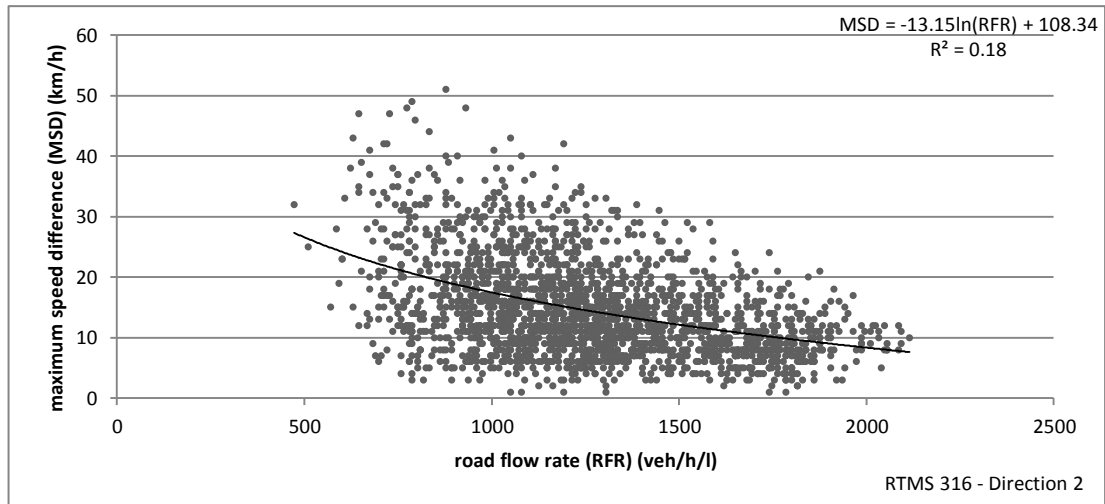
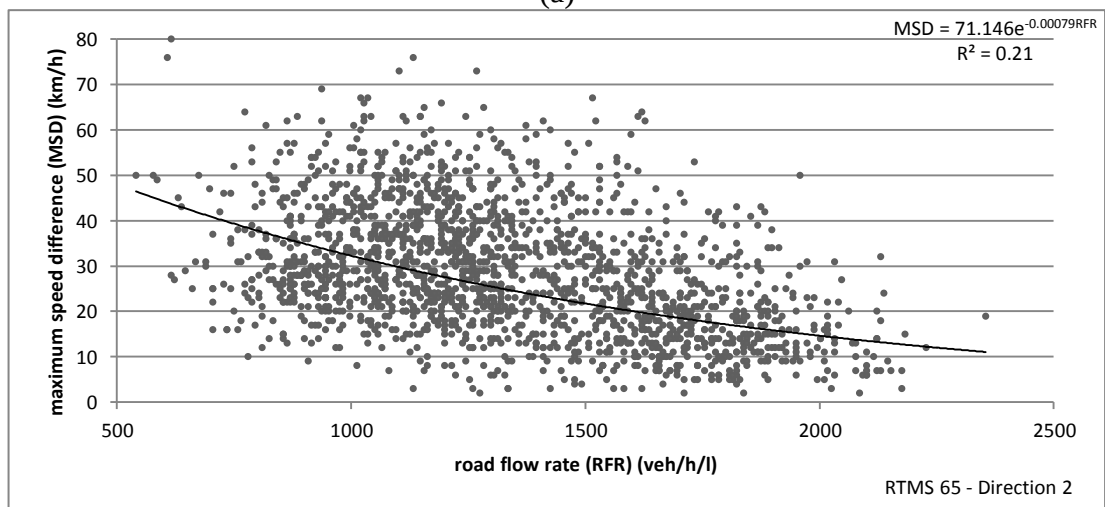


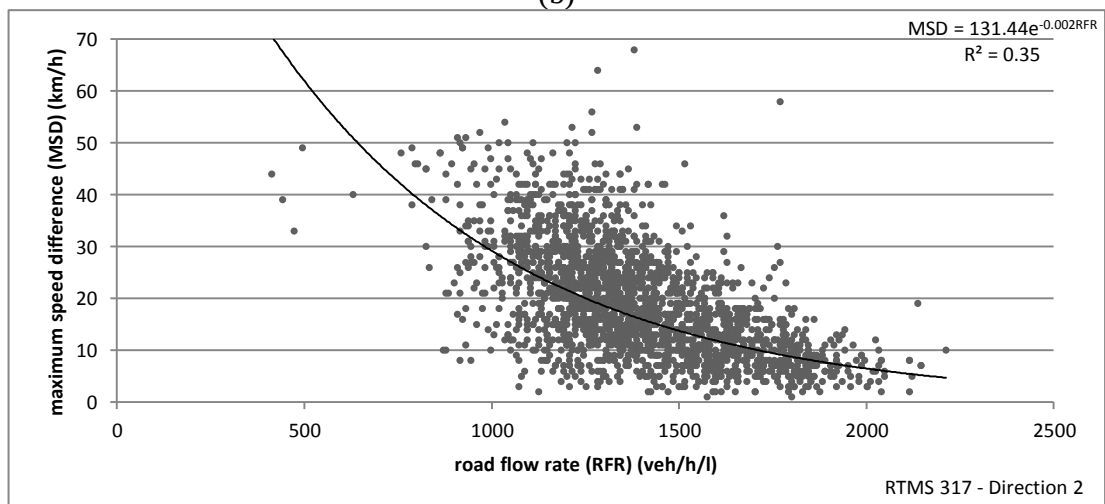
Figure 4.22 : Road flow rate – maximum speed difference across lanes diagrams of Direction 1 for congested area: (a)RTMS 61. (b)RTMS 329.



(a)



(b)



(c)

Figure 4.23 : Road flow rate – maximum speed difference across lanes diagrams of Direction 2 for congested area: (a)RTMS 316. (b)RTMS 65. (c)RTMS 317.

The regression equation and the coefficient of determination (R^2) were obtained by considering and utilizing linear, exponential, logarithmic, 2^o polynomial, and power functions. And, the function with highest R^2 value was selected as the regression equation of each RTMS.

It can be concluded from these equations and their related R^2 values that there is one medium value of R^2 and thus medium value of correlation coefficient (R). This R^2 value is 0.35 belongs to RTMS 317 in Direction 2. Therefore, it is derived that there is moderate relationship between maximum speed difference across lanes and road flow rate for above mentioned RTMS. The maximum speed difference across lanes decreases as the road flow rate increases; similarly, the maximum speed difference across lanes increases when the road flow rate decreases. Related R^2 values of other RTMSs and equations indicate weak relationship between maximum speed difference across lanes and road flow rate.

5. CONCLUSIONS

The results of descriptive statistics at uncongested area show that:

- The far-left-side and far-right-side lanes have the highest and lowest average of speeds, respectively.
- Sundays have the highest and lowest average and standard deviation of speeds, respectively.

The results of K-W tests at uncongested area show that:

- The speeds are statistically different for all lanes.
- At RTMSs of Direction 1, the speed data of the same days of weeks are statistically similar on Thursdays, Fridays and Saturdays.
- Daily speed data of 7 days of week are not coming from the same population.
- When 5 days speed data (Monday to Friday) are compared, it is not possible to conclude that they are statistically similar.
- Saturday and Sunday speed data are statistically different.
- The comparison of speed data of successive days indicates that most similar days are Wednesday and Thursday. At 4 of analyzed 5 RTMSs, the speeds of these days are statistically similar.

The results of K-W tests at congested area indicate that:

- At 2 of 3 RTMSs in Direction 2, the speed at left-side lanes are statistically similar.
- Daily speed data of 7 days of week are not coming from the same population.
- 5 days speed data (Monday to Friday) are statistically different.
- The comparison of speed data of successive days indicates that most similar days are Wednesday and Thursday. At 4 of analyzed 5 RTMSs, the speeds of these days are statistically similar.

The conclusions of 35 K-S tests at road sections indicate that the free flow speed data fit to:

- Normal distribution 20 times (57%)
- Gamma distribution 19 times (54%)
- Lognormal distribution 18 times (51%)
- Gumbel distribution 3 times (9%)

Moreover, at road sections of 2 RTMSs (#329 and #65), FFS data fit to normal distribution on all days of week.

The results of regression analyses at uncongested area show that:

- At 2 of 5 RTMSs, there is moderate relationship between maximum speed difference across lanes and road speed.
- At 2 of analyzed 3 RTMSs in Direction 2, there is moderate relationship between maximum speed difference across lanes and road flow rate. The maximum speed difference across lanes decreases as the road flow rate increases.

The results of regression analyses at congested area show that:

- At 3 of analyzed 5 RTMSs, there is moderate relationship between maximum speed difference across lanes and road speed.
- At 1 of 3 RTMSs in Direction 2, there is moderate relationship between maximum speed difference across lanes and road flow rate. The maximum speed difference across lanes decreases as the road flow rate increases.

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APPENDICES

APPENDIX A: Time – cumulative volume diagrams.

APPENDIX B: K-S tests for different distributions at free speed region.

APPENDIX A

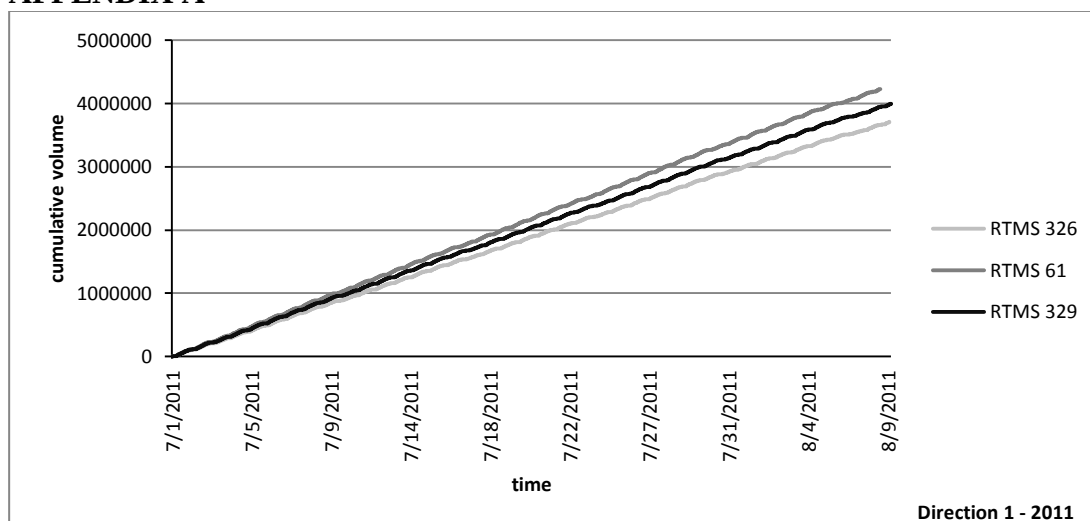


Figure A.1 : Time – cumulative volume diagram on 2011 in Direction 1.

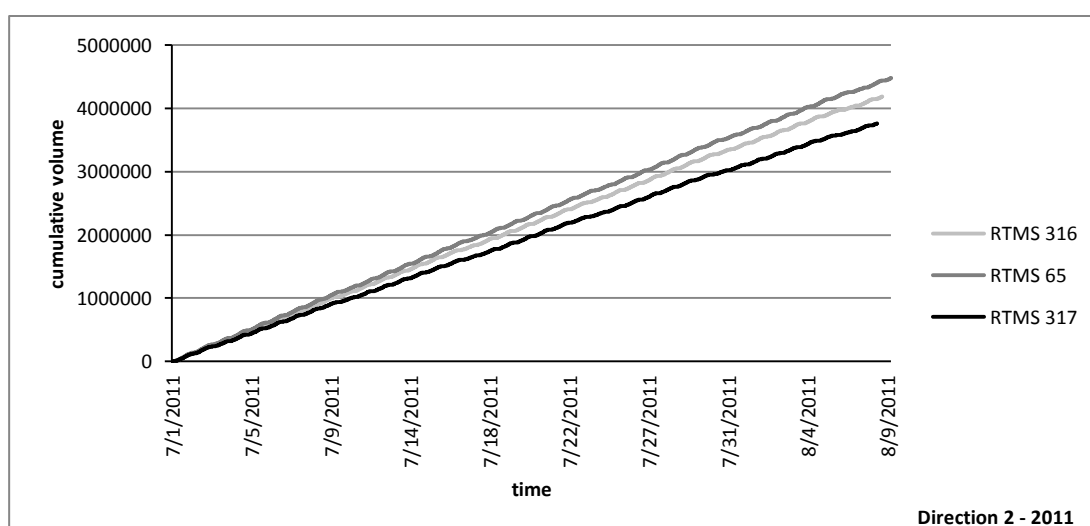


Figure A.2 : Time – cumulative volume diagram on 2011 in Direction 2.

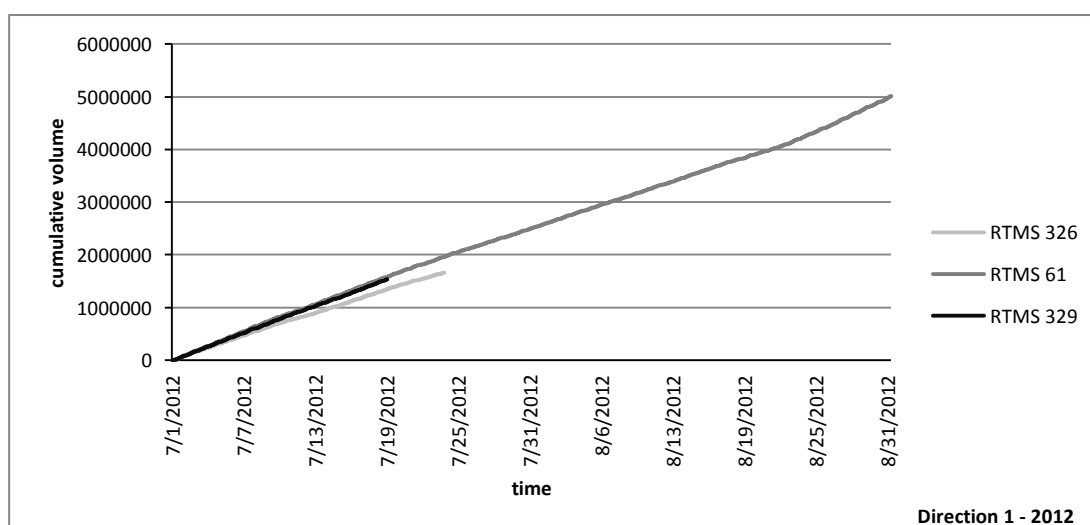


Figure A.3 : Time – cumulative volume diagram on 2012 in Direction 1.

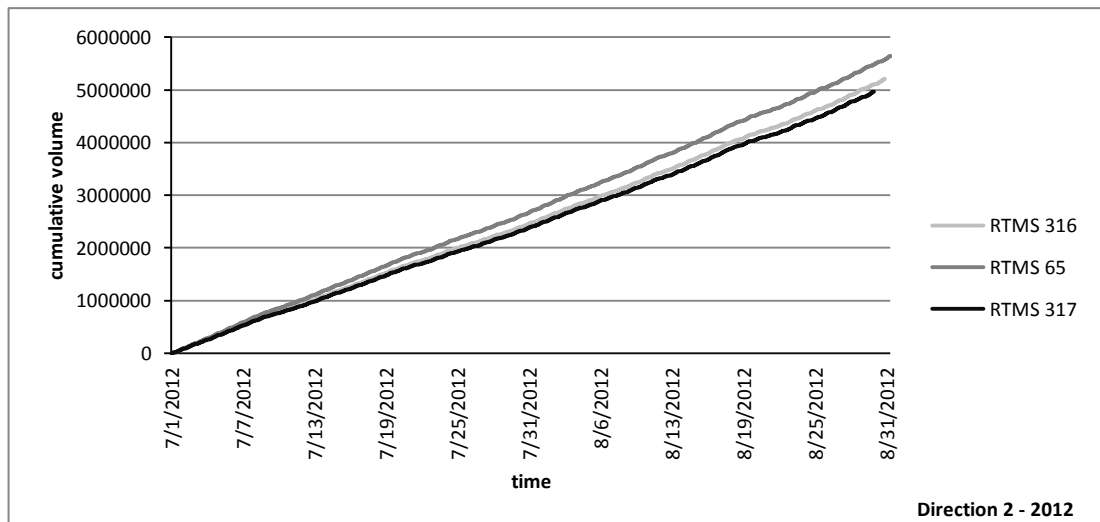


Figure A.4 : Time – cumulative volume diagram on 2012 in Direction 2.

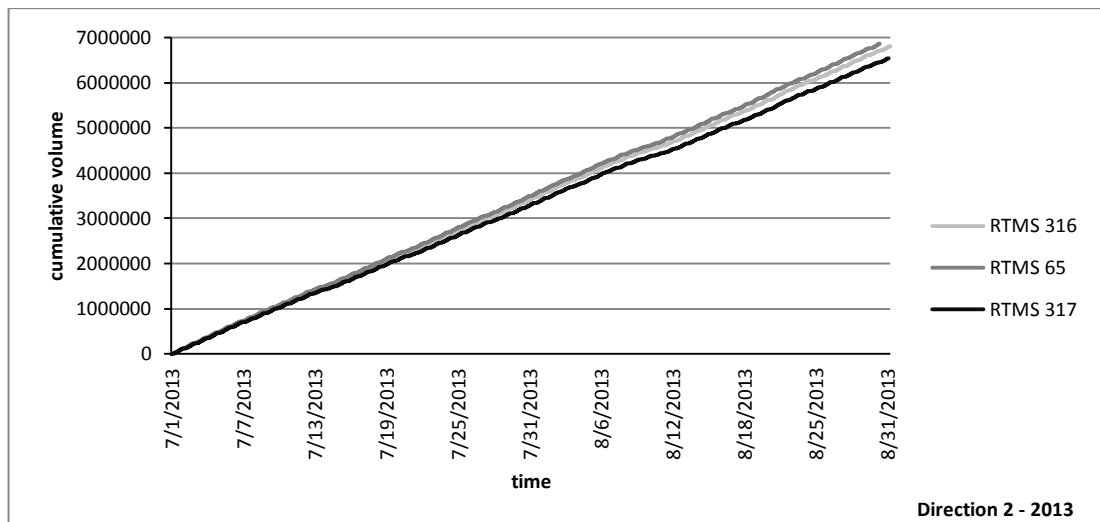


Figure A.5 : Time – cumulative volume diagram on 2013 in Direction 2.

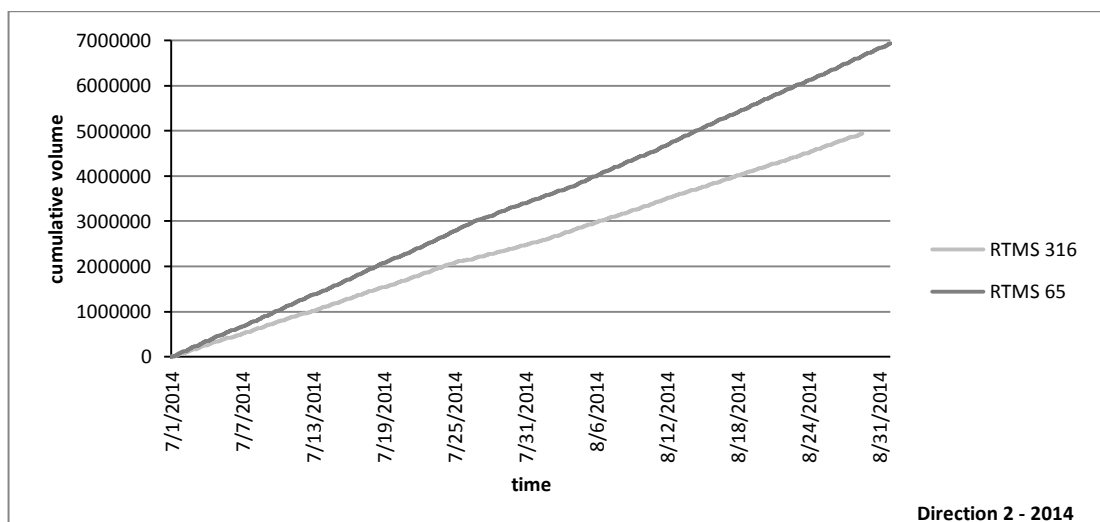


Figure A.6 : Time – cumulative volume diagram on 2014 in Direction 2.

APPENDIX B

Table A.1 : K-S tests for gumbel distribution at free speed region.

Direction	RTMS No.	Lane No.	Mondays		Tuesdays		Wednesdays		Thursdays		Fridays		Saturdays		Sundays	
			K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}
Direction 1	RTMS 61	Lane 1	0.18	0.04	0.20	0.04	0.19	0.04	0.18	0.04	0.20	0.04	0.12	0.04	0.12	0.03
		Lane 2	0.16	0.04	0.14	0.05	0.17	0.04	0.15	0.05	0.17	0.05	0.16	0.05	0.12	0.04
		Lane 3	0.10	0.06	0.11	0.06	0.13	0.05	0.11	0.07	0.14	0.07	0.12	0.07	0.15	0.05
		Lane 4	0.16	0.05	0.14	0.05	0.19	0.05	0.12	0.06	0.14	0.06	0.15	0.06	0.20	0.05
		Road Section	0.11	0.05	0.12	0.05	0.11	0.04	0.10	0.05	0.10	0.06	0.10	0.05	0.12	0.04
	RTMS 329	Lane 1	0.11	0.05	0.11	0.09	0.09	0.07	0.09	0.06	0.13	0.06	0.14	0.05	0.15	0.04
		Lane 2	0.12	0.06	0.11	0.10	0.11	0.07	0.10	0.07	0.13	0.07	0.11	0.06	0.15	0.04
		Lane 3	0.14	0.08	0.1292	0.1289	0.12	0.08	0.12	0.09	0.20	0.10	0.10	0.12	0.15	0.06
		Lane 4	0.21	0.07	0.23	0.10	0.20	0.08	0.22	0.08	0.19	0.08	0.21	0.09	0.21	0.05
		Road Section	0.07	0.06	0.07	0.10	0.070	0.073	0.07	0.07	0.09	0.07	0.11	0.07	0.10	0.04
Direction 2	RTMS 316	Lane 1	0.09	0.02	0.09	0.02	0.09	0.02	0.10	0.03	0.10	0.02	0.11	0.02	0.13	0.02
		Lane 2	0.15	0.03	0.14	0.04	0.08	0.04	0.08	0.04	0.07	0.04	0.10	0.03	0.12	0.03
		Lane 3	0.16	0.05	0.12	0.06	0.13	0.06	0.0612	0.0613	0.12	0.05	0.13	0.04	0.15	0.03
		Lane 4	0.15	0.04	0.14	0.06	0.15	0.06	0.15	0.06	0.16	0.05	0.15	0.04	0.19	0.03
		Road Section	0.15	0.04	0.09	0.05	0.039	0.044	0.07	0.05	0.09	0.04	0.07	0.03	0.10	0.03
	RTMS 65	Lane 1	0.12	0.02	0.13	0.02	0.13	0.02	0.13	0.02	0.13	0.02	0.12	0.02	0.11	0.02
		Lane 2	0.10	0.03	0.14	0.03	0.15	0.03	0.16	0.03	0.15	0.03	0.12	0.03	0.09	0.03
		Lane 3	0.11	0.04	0.11	0.04	0.11	0.04	0.09	0.04	0.12	0.03	0.10	0.04	0.12	0.03
		Lane 4	0.13	0.03	0.10	0.03	0.10	0.03	0.09	0.03	0.10	0.03	0.08	0.03	0.13	0.03
		Road Section	0.08	0.03	0.07	0.03	0.08	0.03	0.10	0.03	0.09	0.03	0.09	0.03	0.07	0.03
	RTMS 317	Lane 1	0.08	0.03	0.08	0.03	0.07	0.03	0.06	0.03	0.08	0.03	0.11	0.02	0.12	0.02
		Lane 2	0.15	0.03	0.10	0.04	0.09	0.03	0.06	0.04	0.06	0.03	0.10	0.03	0.14	0.02
		Lane 3	0.19	0.04	0.16	0.05	0.15	0.04	0.13	0.05	0.16	0.04	0.18	0.04	0.17	0.03
		Lane 4	0.16	0.04	0.15	0.04	0.16	0.04	0.16	0.05	0.16	0.04	0.16	0.03	0.15	0.03
		Road Section	0.15	0.03	0.09	0.04	0.06	0.04	0.06	0.04	0.06	0.04	0.08	0.03	0.11	0.03

Table A.2 : K-S tests for exponential distribution at free speed region.

Direction	RTMS No.	Lane No.	Mondays		Tuesdays		Wednesdays		Thursdays		Fridays		Saturdays		Sundays	
			K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}
Direction 1	RTMS 61	Lane 1	0.56	0.04	0.55	0.04	0.54	0.04	0.55	0.04	0.56	0.04	0.56	0.04	0.56	0.03
		Lane 2	0.57	0.04	0.56	0.05	0.56	0.04	0.56	0.05	0.56	0.05	0.56	0.05	0.56	0.04
		Lane 3	0.56	0.06	0.57	0.06	0.56	0.05	0.57	0.07	0.56	0.07	0.57	0.07	0.55	0.05
		Lane 4	0.58	0.05	0.58	0.05	0.57	0.05	0.57	0.06	0.59	0.06	0.58	0.06	0.59	0.05
	RTMS 329	Road Section	0.58	0.05	0.58	0.05	0.58	0.04	0.57	0.05	0.58	0.06	0.59	0.05	0.58	0.04
		Lane 1	0.54	0.05	0.52	0.09	0.53	0.07	0.55	0.06	0.53	0.06	0.56	0.05	0.57	0.04
		Lane 2	0.54	0.06	0.55	0.10	0.54	0.07	0.55	0.07	0.55	0.07	0.58	0.06	0.58	0.04
		Lane 3	0.58	0.08	0.58	0.13	0.58	0.08	0.59	0.09	0.56	0.10	0.59	0.12	0.60	0.06
Direction 2	RTMS 316	Lane 4	0.59	0.07	0.59	0.10	0.60	0.08	0.60	0.08	0.59	0.08	0.60	0.09	0.61	0.05
		Road Section	0.58	0.06	0.57	0.10	0.57	0.07	0.59	0.07	0.57	0.07	0.60	0.07	0.60	0.04
	RTMS 65	Lane 1	0.55	0.02	0.55	0.02	0.55	0.02	0.54	0.03	0.54	0.02	0.54	0.02	0.57	0.02
		Lane 2	0.53	0.03	0.53	0.04	0.52	0.04	0.52	0.04	0.52	0.04	0.54	0.03	0.56	0.03
		Lane 3	0.57	0.05	0.58	0.06	0.56	0.06	0.58	0.06	0.57	0.05	0.58	0.04	0.59	0.03
		Lane 4	0.60	0.04	0.61	0.06	0.60	0.06	0.60	0.06	0.60	0.05	0.60	0.04	0.60	0.03
	RTMS 317	Road Section	0.58	0.04	0.58	0.05	0.58	0.04	0.58	0.05	0.58	0.04	0.58	0.03	0.59	0.03
		Lane 1	0.57	0.02	0.57	0.02	0.57	0.02	0.58	0.02	0.58	0.02	0.58	0.02	0.58	0.02
		Lane 2	0.57	0.03	0.56	0.03	0.55	0.03	0.55	0.03	0.55	0.03	0.56	0.03	0.57	0.03
		Lane 3	0.57	0.04	0.57	0.04	0.57	0.04	0.57	0.04	0.57	0.03	0.57	0.04	0.57	0.03
	RTMS 317	Lane 4	0.54	0.03	0.54	0.03	0.56	0.03	0.56	0.03	0.55	0.03	0.56	0.03	0.55	0.03
		Road Section	0.59	0.03	0.59	0.03	0.59	0.03	0.58	0.03	0.59	0.03	0.59	0.03	0.59	0.03
		Lane 1	0.56	0.03	0.57	0.03	0.57	0.03	0.56	0.03	0.56	0.03	0.55	0.02	0.57	0.02
		Lane 2	0.54	0.03	0.55	0.04	0.54	0.03	0.54	0.04	0.54	0.03	0.55	0.03	0.57	0.02
		Lane 3	0.57	0.04	0.56	0.05	0.56	0.04	0.56	0.05	0.57	0.04	0.57	0.04	0.58	0.03
		Lane 4	0.59	0.04	0.60	0.04	0.58	0.04	0.60	0.05	0.60	0.04	0.59	0.03	0.60	0.03
		Road Section	0.58	0.03	0.58	0.04	0.58	0.04	0.58	0.04	0.58	0.04	0.58	0.03	0.59	0.03

Table A.3 : K-S tests for uniform distribution at free speed region.

Direction	RTMS No.	Lane No.	Mondays		Tuesdays		Wednesdays		Thursdays		Fridays		Saturdays		Sundays	
			K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}	K-S	(K-S) _{cri.}
Direction 1	RTMS 61	Lane 1	0.49	0.04	0.42	0.04	0.34	0.04	0.45	0.04	0.45	0.04	0.41	0.04	0.40	0.03
		Lane 2	0.46	0.04	0.41	0.05	0.36	0.04	0.45	0.05	0.31	0.05	0.36	0.05	0.26	0.04
		Lane 3	0.28	0.06	0.33	0.06	0.40	0.05	0.32	0.07	0.25	0.07	0.21	0.07	0.21	0.05
		Lane 4	0.47	0.05	0.35	0.05	0.25	0.05	0.31	0.06	0.32	0.06	0.34	0.06	0.43	0.05
	RTMS 329	Road Section	0.46	0.05	0.46	0.05	0.47	0.04	0.47	0.05	0.33	0.06	0.47	0.05	0.23	0.04
		Lane 1	0.39	0.05	0.33	0.09	0.27	0.07	0.26	0.06	0.32	0.06	0.26	0.05	0.29	0.04
		Lane 2	0.37	0.06	0.26	0.10	0.31	0.07	0.23	0.07	0.41	0.07	0.24	0.06	0.38	0.04
		Lane 3	0.44	0.08	0.25	0.13	0.31	0.08	0.15	0.09	0.48	0.10	0.29	0.12	0.33	0.06
Direction 2	RTMS 316	Lane 4	0.64	0.07	0.54	0.10	0.54	0.08	0.52	0.08	0.46	0.08	0.43	0.09	0.70	0.05
		Road Section	0.46	0.06	0.37	0.10	0.33	0.07	0.26	0.07	0.45	0.07	0.23	0.07	0.57	0.04
	RTMS 65	Lane 1	0.18	0.02	0.18	0.02	0.21	0.02	0.20	0.03	0.16	0.02	0.16	0.02	0.32	0.02
		Lane 2	0.27	0.03	0.22	0.04	0.20	0.04	0.17	0.04	0.22	0.04	0.26	0.03	0.21	0.03
		Lane 3	0.33	0.05	0.33	0.06	0.40	0.06	0.17	0.06	0.29	0.05	0.24	0.04	0.29	0.03
		Lane 4	0.32	0.04	0.28	0.06	0.47	0.06	0.24	0.06	0.40	0.05	0.63	0.04	0.67	0.03
	RTMS 317	Road Section	0.31	0.04	0.27	0.05	0.22	0.04	0.27	0.05	0.20	0.04	0.29	0.03	0.27	0.03
		Lane 1	0.41	0.02	0.47	0.02	0.39	0.02	0.42	0.02	0.52	0.02	0.54	0.02	0.36	0.02
		Lane 2	0.24	0.03	0.31	0.03	0.25	0.03	0.24	0.03	0.23	0.03	0.32	0.03	0.21	0.03
		Lane 3	0.32	0.04	0.27	0.04	0.25	0.04	0.26	0.04	0.26	0.03	0.36	0.04	0.23	0.03
	RTMS 317	Lane 4	0.27	0.03	0.21	0.03	0.23	0.03	0.20	0.03	0.14	0.03	0.24	0.03	0.27	0.03
		Road Section	0.21	0.03	0.26	0.03	0.25	0.03	0.35	0.03	0.29	0.03	0.28	0.03	0.23	0.03
		Lane 1	0.18	0.03	0.31	0.03	0.29	0.03	0.23	0.03	0.22	0.03	0.16	0.02	0.24	0.02
		Lane 2	0.21	0.03	0.19	0.04	0.20	0.03	0.17	0.04	0.19	0.03	0.24	0.03	0.35	0.02
		Lane 3	0.32	0.04	0.40	0.05	0.35	0.04	0.27	0.05	0.32	0.04	0.32	0.04	0.38	0.03
		Lane 4	0.42	0.04	0.48	0.04	0.45	0.04	0.49	0.05	0.43	0.04	0.42	0.03	0.56	0.03
		Road Section	0.37	0.03	0.38	0.04	0.32	0.04	0.19	0.04	0.25	0.04	0.29	0.03	0.33	0.03

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