ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

METHODOLOGY DEVELOPMENT FOR THE CONSTRUCTION OF A DRIVING CYCLE IN ORDER TO DETERMINE THE EXHAUST EMISSIONS OF ROAD VEHICLES

Ph.D. THESIS

Cenk DİNÇ

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

KARAYOLLARI TAŞITLARINDAN KAYNAKLANAN EGZOZ GAZI EMİSYONLARININ BELİRLENMESİ İÇİN ŞEHİR ÇEVRİMİ OLUŞTURMA METODOLOJİSİNİN GELİŞTİRİLMESİ

DOKTORA TEZİ

Cenk DİNÇ
(503062022)

Makina Mühendisliği Anabilim Dalı

Makina Mühendisliği Programı

Tez Danışmanı: Prof. Dr. Cem SORUŞBAY

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Cenk DİNÇ, **a Ph.D.** student of ITU **Graduate School of Science Engineering And Technology** student ID **503062022**, successfully defended the **thesis** entitled "**METHODOLOGY DEVELOPMENT FOR THE CONSTRUCTION OF A DRIVING CYCLE IN ORDER TO DETERMINE THE EXHAUST EMISSIONS OF ROAD VEHICLES**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Prof. Dr. Cem SORUŞBAY** ....
İstanbul Technical University

Jury Members : **Prof.Dr. Metin ERGENEMAN** ....
İstanbul Technical University

Prof. Dr. İrfan YAVAŞLIOL ....
Yıldız Technical University

Prof. Dr. Kadir ALP ....
İstanbul Technical University

Doç. Dr. Hakan SOYHAN ....
Sakarya University

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To Duygu,

FOREWORD

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TABLE OF CONTENTS

Page

ABBREVIATIONS

ADC : Athens Driving Cycle
AUC : Australian Urban Cycle
ECM : Electronic Control Module
FTP : Federal Test Procedure
GHG : Greenhouse Gases
GPS : Global Positioning System
IC : Internal Combustion
IDC : İstanbul Driving Cycle
NEDC : New European Driving Cycle
NYCC : New York City Cycle
RTMS : Remote Traffic Monitoring System
UC : Uncontrolled (pre emission regulations)

LIST OF TABLES

Page

LIST OF FIGURES

Page

METHODOLOGY DEVELOPMENT FOR THE CONSTRUCTION OF A DRIVING CYCLE IN ORDER TO DETERMINE THE EXHAUST EMISSIONS OF ROAD VEHICLES

SUMMARY

Vehicle exhaust emissions and emission factors are strongly affected by driving conditions; therefore identifying the driving patterns in a specific region plays a crucial role for the accurate estimation of vehicle emissions. The driving pattern in a specific region can be represented as a driving cycle, which is a vehicle speed-time profile. Driving conditions can then be simulated on a laboratory chassis dynamometer with the aid of this speed-time profile in order to evaluate fuel consumption, exhaust emissions and vehicle emission factors.

In this study, a new methodology is proposed to develop a real-world driving cycle for the estimation of greenhouse gas emissions and a case study is put into practice for the city of İstanbul. Real world statistical data is collected and sequenced into micro-trips. Series of micro-trips are selected with a quasi-random approach until the traveled distance of the driving cycle reaches a predefined limit. Each developed driving cycle is evaluated with respect to the real world test data by using specific comparison criteria and the driving cycle that best represents the driving characteristics of the specific region is chosen as the final driving cycle.

Selecting representative routes is the first stage in driving cycle construction. This is one of the most significant stages in driving cycle development because this stage directly effects how well the final driving cycle will represent the specific regional driving characteristics in the end. The driving routes are selected with a two-stage process. In the first stage, the commonly used routes of the region are identified as base routes. Real world driving data is collected in the base routes. In the second stage, every selected route is analyzed with respect to some performance parameters with the aid of a regional transportation model. After the completion of this analysis, only the specific parts of the routes, which have similar performance parameters compared to the region, are not taken into account for driving cycle generation.

Real world driving data is segmented into smaller elements called macro-trips. The driving cycle is developed with successive random selections of these macro-trips. Prior to the initialization of quasi-random selection process, some parameters that define the characteristics of the driving cycle need to set. These are the driving cycle constraints: cycle length, number of idle phases and idling percentage. After the segmentation of the driving data into macro-trips and the identification of driving cycle constraints, the quasi-random selection process is initiated. This process is constituted of consecutive addition of macro-trips. For each addition, the driving cycle development algorithm searches for macro-trips whose initial speeds are equal to the final speed of the latest added macro-trip. The selection process is continued until the pre-defined length of the travelling unit is reached.

A constructed driving cycle is stored in memory only if it has less than 5% error related to all assessment criteria and it represents the regional driving characteristics more accurately than all previous candidate driving cycles. After a considerable number of iterations are completed, the most representative one is chosen as the final driving cycle. The parameters that are used to quantify the representativeness of a candidate driving cycle are called assessment criteria. The assessment criteria utilized in this thesis are percentage of idling, average speed, average acceleration, average deceleration, average positive specific power and average negative specific power.

As a case study, a real world driving cycle is generated for İstanbul based on the methodology presented. In order to create a real world driving cycle, real world driving data is collected in actual traffic conditions. Real world driving data is collected in the base routes with a Renault Megane passenger car, equipped with a data logger and a GPS system. The data logger is interfaced with the electronic control module (ECM) of the vehicle and records vehicle speed as a function of time. Real world traffic data is collected in morning and evening peak traffic conditions as well as off-peak conditions; both in weekdays and weekends. The final driving cycle generated for İstanbul is named as İstanbul Driving Cycle (IDC). IDC is compared with legislative cycles in terms of fuel consumption and exhaust emissions. As a part of another study, the dynamometer tests are carried out with thirty passenger cars with spark ignition engine of different model year and emission control technology. The model years and emission control technologies of the test vehicles are selected to reflect the passenger car fleet with spark ignition engine in Turkey. The fuel consumption values obtained with IDC are higher compared to the legislative cycles for every emission control technology. Considering Federal Test Procedure (FTP75) cycle, the fuel consumption values obtained with IDC are 15 to 30% higher. Considering New European Driving Cycle (NEDC), the fuel consumption values obtained with IDC are 4 to 12% higher for different emission control technologies. These results show that, the regional driving characteristics of İstanbul; hence, the exhaust emissions cannot be represented accurately with legislative cycles of FTP75 and NEDC.

In the last chapter, importance of road grade resistance and its integration into driving cycles is discussed. Real world driving data is collected in actual traffic conditions, where there is altering road grade. The driving cycle which is generated from this real world driving data is simulated on a flat chassis dynamometer. In this situation, the effect of road grade is not included. Consequently, the regional exhaust emission factors cannot be estimated accurately.

There can be two different solution proposals to embed the road grade effect into a driving cycle. The first one is to add or subtract the extra force related to the grade power into the chassis dynamometer via software or hardware. This is possible since the grade of every micro-trip in the driving cycle is known. However, this requires additional software or hardware update and is not practical to apply in conventional chassis dynamometer testing facility. In this thesis, a universal solution to this problem is presented. After the driving cycle is generated, micro-trips are modified such that the grade effect is embedded into the conventional driving cycle form.

The modification of the driving cycle trip properties can be carried out in two different ways. The trip properties can be modified in terms of velocity or time. Modifying the velocities of micro-trips is not preferred due to two main reasons. The first reason is that modifying the velocity of the micro-trips alters the average velocity of the micro-trip, which can affect the exhaust emission characteristics of the micro-trip. The second reason is that the micro-trips in a driving cycle are coupled sequentially. If the initial or final velocity of an individual micro-trip is altered, that also effects the preceding or the next micro-trip, which requires a complex iterative modification approach. When these disadvantages of modifying micro-trip velocities are taken into consideration, it is decided to modify micro-trips only with respect to time in this thesis.

After the driving cycle is generated, micro-trips are modified with respect to time such that the grade work required for each micro-trip is included in the chassis dynamometer tests. This may not be realized for every micro-trip because the time modification process may lead to unrealistic acceleration values for some micro-trips. Hence, the grade work is not represented completely for these specific micro-trips. For such a case, the part of the grade work that is not represented is stored as residual work and reflected into the final error term. With this approach, the grade work can be represented on a conventional chassis dynamometer without any hardware or software update.

In conclusion, a methodology is developed for the construction of a driving cycle with quasi-random micro-trip approach and a practical application is conducted for the city of İstanbul. The final driving cycle is named as İstanbul Driving Cycle (IDC) IDC is compared with legislative cycles of Federal Test Procedure (FTP-75) and New European Driving Cycle (NEDC) in terms of fuel consumption and exhaust emissions. The dynamometer tests are carried out with thirty passenger cars with spark ignition engine of different model year and emission control technology. The model years and emission control technologies of the test vehicles are selected to reflect the passenger car fleet with spark ignition engine in Turkey. It is seen that higher exhaust gas emissions are measured with IDC, which shows that, the regional driving characteristics of İstanbul; hence the exhaust emissions cannot be represented accurately with legislative cycles of FTP75 and NEDC. Additionally, a methodology is presented to represent the grade effect of real world driving conditions on a flat chassis dynamometer testing facility. With this method, the grade work of any trajectory can be represented on a conventional chassis dynamometer without any hardware or software update.

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ÖZET

Karayolları taşıtlarından kaynaklanan egzoz gazları emisyonu ve emisyon faktörleri taşıtın kullanım koşullarına göre oldukça büyük bir değişiklik göstermektedir. Bu yüzden, belli bir bölgede karayolları taşıtlarından kaynaklanan emisyonların hassas olarak tahmin edilebilmesi, o bölgedeki taşıt kullanım karakteristiğinin ne kadar hassas olarak tanımlanabildiğine bağlıdır. Bir bölgedeki taşıt kullanım karakteristiği şehir çevrimi olarak adlandırılan bir hız-zaman profili ile temsil edilir. Şasi dinamometresinde bu hız-zaman profilinin aracılığıyla gerçek hayattaki sürüş koşulları temsil edilip taşıtın yakıt tüketimi ve egzoz emisyon faktörleri bulunabilir.

Şehir çevrimleri oluşturulma yöntemine göre modal çevrimler ya da gerçek çevrimler olarak ikiye ayrılmaktadır. Modal çevrimler suni sürüş profillerinin birleştirilmesiyle oluşturulmuştur. Çok düzgün hızlanma ve yavaşlama profillerine sahiptirler ve gerçek sürüş koşullarının dinamik karakteristiğini taşımazlar. Gerçek çevrimler ise gerçek trafik koşullarında ölçülmüş hız datalarının birleştirilmesiyle oluşturulmuştur, dolayısıyla daha dinamik ve gerçekçi karakterdedirler.

Şehir çevrimleri kullanım amacına göre de iki farklı şekilde sınıflandırılır. Bir grup trafiğe çıkacak araçların denetlenmesine yönelik olarak oluşturulan ve homologasyon testlerinde kullanılan çevrimlerdir. Diğer grup ise, belli bir bölgedeki trafik karakteristiğini anlamak ve o bölgedeki egzoz gazı emisyonlarının gerçekçi olarak tahmin edilebilmesi için oluşturulan çevrimlerdir.

Bu tezde belli bir bölgedeki egzoz gaz emisyonlarının tahminini sağlayacak gerçek bir çevrim oluşturulma metodolojisi önerilmektedir. Daha sonrada bu metodolojinin pratik bir uygulaması olarak İstanbul şehir çevrimi oluşturulmaktadır. Bu çevrimin oluşturulması için öncelikle gerçek trafik koşulları içerisinde sürüş datası toplanmaktadır. Toplanan bu data mikro yolculuk olarak adlandırılan daha küçük parçalara bölünmektedir. Sonrasında bu mikro yolculuklar, yarı-rastgele bir çekiliş yöntemiyle, daha önce belirlenen çevrim uzunluğu ya da zamanına ulaşılana kadar ard arda eklenerek çevrim oluşturulmaktadır. Ard arda ekleme metodunun tamamen rastgele olarak adlandırılmamasının nedeni önceden belirlenen bazı çevrim özellikleri sağlanacak şekilde bazı eklemelerin rastgele olmamasıdır. Bu şekilde birçok çevrim üretilmektedir. Üretilen çevrimlerin her biri gerçek sürüş datasının özellikleri ile karşılaştırılmaktadır. Bu karşılaştırma yapılırken belli bazı kriterler dikkate alınmaktadır. Bunlar aracın rölantide çalışıtığı zaman diliminin çevrim süresine oranı, çevrim boyunca ortalama hız, ortalama pozitif ve negatif ivme, ortalama pozitif ve negatif özgül güçlerdir. Bu parametrelere yapılan karşılaştırma sonucu, bölgenin sürüş karakteristiğini en yakın biçimde sağlayan çevrim o bölgenin şehir çevrimi olarak belirlenmektedir.

Çevrim oluşturmadaki ilk adım bölgeyi temsil niteliği olan rotaların seçilmesidir. Bu bir şehir çevrimi oluşturmak için en önemli adımlardan bir tanesidir çünkü oluşturulan çevrimin temsil niteliği bu rotalarda toplanan sürüş datasına göre değerlendirilmektedir. Bir başka deyişle, belli rotalarda sürüş datası toplayarak bir çevrim oluşturulduğunda, o çevrimin söz konusu rotaları ne kadar iyi bir şekilde temsil edebildiği değerlendirilebilir. Fakat oluşturulan çevrimin, ilgili bölgenin sürüş karakteristiğini yansıtması için öncelikle seçilen rotalar bölgenin sürüş karakteristiği ile uyumlu olmalıdır. Rotaların seçimi için iki kademeli bir yöntem uygulanmaktadır. İlk aşamada yoğun olarak kullanılan ana arterler seçilmektedir. Bu yollar seçilirken, bu yolların farklı trafik sürüş koşullarını barındırdığına bakılmaktadır. Bu yollar hem çok sıkışık bir trafiğe sahip şehiriçi yoğun kentsel bölgeleri, hem de yüksek hızlara çıkılabilen otoyolları kapsamalıdır. Bu seçilen rotalarda gerçek trafik sürüş datası toplantıkdan sonra ikinci aşamaya geçilmektedir. Bu da seçilen rotalarda bir eliminasyona gidilmesiyle yapılmaktadır. Seçilen rotaların bölgenin sürüş özelliklerini ne ölçüde yansıttığı bölgenin ulaşım modeliyle kontrol edilmektedir. Buna göre, rotaların sadece bölgenin belli özelliklerini sağladığı bölgeleri şehir çevrimi oluşturulmak üzere dikkate alınmakta, diğer bölgeler elenmektedir.

Şehir çevrimi oluşturulmaya başlanmadan önce çevrimin bazı parametreleri belirlenmektedir. Bunlar çevrimin uzunluğu, çevrimde kaç adet rölanti fazı bulunacağı ve bu rölanti fazlarının şehir çevrimi içerisinde ne yüzde olarak ne kadar zaman kapsayacağıdır. Yarı-rastgele metod ile çekilişler yapılırken bu parametreler dikkate alınmaktadır. Çekiliş işlemi mikro yolculukların ard arda eklenmesiyle yapılmaktadır. Eklenecek yeni bir mikro yolculuk seçilirken, bu mikro yolculuğun ilk hızının bir önceki mikro yolculuğunun son hızına eşit olması gerekmektedir. Bunun dışında, daha önce belirlenen parametrelere göre çevrimin rölanti moduna girmesi gerekiyorsa, algoritma son hızı sıfır olan mikro yolculukları seçmeye çalışmaktadır. Bu çekiliş ve ard arda ekleme işlemi önceden belirlenen çevrim uzunluğuna ulaşılana kadar devam etmektedir.

Oluşturulan her çevrim yukarıda bahsedilen kriterlere göre değerlendirilmekte ve bu yöntemle bölgeyi ne ölçüde temsil ettiği anlaşılmaktadır. Oluşturulan çevrimlerden, sadece her kriter için 5%' den az hataya sahip olanları hafızada tutulmaktadır. Hata oranı daha büyük olan çevrimler kaydedilmemektedir. Belli sayıda iterasyon tamamlandıktan sonra, hafızaya kaydedilen çevrimlerden bölgenin sürüş karakteristiğini en yakın olarak yansıtan çevrim şehir çevrimi olarak seçilmektedir.

Şehir çevrimi oluşturmak için yukarıdaki gibi bir metodoloji tanımlandıktan sonra pratik bir uygulama İstanbul için yapılmaktadır. İstanbul için gerçek bir şehir çevrimi oluşturulması için, İstanbul trafiğinde sürüş datası toplanmaktadır. Belirlenen rotalarda, veri toplayıcısına ve GPS sistemine sahip bit Renault Megane marka bir araçla data toplanmaktadır. Veri toplayıcısı aracın elektronik kontrol modülüne bağlıdır ve araç hızını zamana bağlı olarak kaydetmektedir. Sürüş datası sabah, öğle, akşam olmak üzere, hem haftaiçleri hem de haftasonları toplanmaktadır. Daha sonra bu çalışmada tanımlanan metodolojiye göre İstanbul için bir şehir çevrimi oluşturulmakta ve İstanbul Driving Cycle (IDC) olarak adlandırılmaktadır. Oluşturulan bu İstanbul çevrimi, yasal homologasyon onaylarının verildiği Federal test prosedürü (FTP75) ve Avrupa çevrimiyle (NEDC) karşılaştırılmaktadır. Farklı yaşta ve farklı emisyon teknolojilerine sahip araçlar şasi dinamometresinde bu üç çevrime göre koşturulmakta ve sonuçlar karşılaştırılmaktadır. Koşturulan araç seçilirken, bu araçların yaşlarının ve emisyon teknolojilerinin Türkiye' deki araç filosunu temsil ettiğine özen gösterilmektedir. Test sonuçlarına göre, İstanbul çevrimiyle elde edilen yakıt tüketim değerleri FTP prosedürüne göre %15 ila %30, Avrupa çevrimine göre de %4 ila %12 oranında daha yüksek yakıt tüketimi sonuçları vermektedir. Buradan da anlaşılacağı üzere, belirli bir bölgedeki sürüş karakteristiği ve bunun sonucu olan yakıt tüketimi ve emisyonlar, FPT ve NEDC gibi homologatif çevrimlerle hassas olarak tespit edilememektedir. Belirli bir bölgedeki sürüş karakteristiği ortaya çıkarmanın en hassas yolu o bölge için spesifik bir gerçek şehir çevrimi oluşturmaktır.

Tezin son bölümünde ise, şehir çevrimi oluşturmada yokuş direncinin önemi ve bunun şehir çevrimine entegrasyonu için bir metod önerilmektedir. Gerçek sürüş datasının toplandığı yol koşullarında yolun bir eğimi vardır fakat, bu sürüş datasından oluşturulan şehir çevrimi düz bir şasi dinamometresinde koşturulduğu için bu eğimin etkisi dikkate alınmamış olur. Böylece yokuş direncinin emisyon faktörlerine etkisi değerlendirilmemiş olur.

Yoldaki yokuş direncinin çevrim içerisine eklenmesi için iki farklı yöntem olabilir. Bunlardan bir tanesi, eğimden kaynaklanan direnç kuvvetinin dinamometrede tanımlanmasıyla olabilir. Fakat bu çok basit bir işlem değildir ve konvansiyonel dinamometrelerde bunu yapabilmek için hem donanım hem de yazılım olarak değişiklikler gerekmektedir. Dolayısıyla bu yöntem konvansiyonel bir dinamometrede uygulanabilecek şekilde pratik bir yöntem değildir. Bu tezde bu problemle ilgili daha universal bir çözüm önerilmektedir. Şehir çevrimi geliştirildikten sonra, çevrimi oluşturan her mikro yolculuk yokuş direncini içerecek şekilde düzeltilmektedir.

Mikro yolculukların düzeltilmesi iki farklı yol ile yapılabilir. Bunlardan bir tanesi mikro tribin zamanı ile oynamak, diğeri de hız değerleriyle oynamaktır. Bu tezde hız ile oynamak tercih edilmemiştir. Bunun nedeni çevrimin ortalama hız karakterinin korunmak istenmesidir. Bir diğer neden de, herhangi bir mikro yolculuğun hızı ile oynandığında, onu takip eden mikro yolculuğunda hızı da değiştirilmek durumunda olacağından algoritma karmaşık bir hal almaktadır.

Şehir çevrimi geliştirilmesi tamamlandıktan ve en iyi çevrim seçildikten sonra çevrimi oluşturan mikro yolculukların zamanları, yol eğiminden kaynaklanan iş dahil edilecek şekilde düzeltilmektedir. Bu her mikro yolculuk için sağlanamayabilir çünkü zamana göre düzeltme yapıldığı için, bazı durumlarda gerçekçi olmayan ivme değerleriyle karşılaşılmaktadır. Bu şekildeki bir yaklaşımla, herhangi bir yazılım ve donanım yenilemesine gerek kalmadan, konvansiyonel bir şasi dinamometresinde, yokuş direnci yedirilmiş şehir çevrimi koşturularak, yokuş direncinin yakıt tüketimi ve emisyonlara etkisi gözlenebilmektedir.

Sonuç olarak bu tezde, yarı-rastgele yaklaşımla gerçek bir şehir çevrimi oluşturulması için bir metodoloji geliştirilmekte ve bunun pratik uygulaması da İstanbul için yapılmaktadır. Elde edilen şehir çevrimi İstanbul Driving Cycle (IDC) olarak isimlendirilmekte ve bu çevrim homologatif FPT ve NEDC çevrimleriyle karşılaştırılmaktadır. Şasi dinamometresinde üç farklı çevrimle yapılan test sonuçlarına göre, İstanbul çevrimiyle elde edilen yakıt tüketim değerleri FTP prosedürüne göre %15 ila %30, Avrupa çevrimine göre de %4 ila %12 oranında daha yüksek yakıt tüketimi sonuçları vermektedir. Buradan da anlaşılacağı üzere, belirli bir bölgedeki sürüş karakteristiği ve bunun sonucu olan yakıt tüketimi ve emisyonlar, FTP ve NEDC gibi homologatif çevrimlerle hassas olarak tespit edilememektedir. Belirli bir bölgedeki sürüş karakteristiği ortaya çıkarmanın en hassas yolu o bölge için spesifik bir gerçek şehir çevrimi oluşturmaktır. Bu çalışmaya ek olarak, tezin son bölümünde yolun yokuş direncinin şehir çevrimine entegrasyonu için bir metod önerilmektedir. Metodun özü, çevrimi oluşturan mikro yolculukların zamanlarının, yol eğiminden kaynaklanan iş dahil edilecek şekilde düzeltilmesidir. Bu sayede düzeltilmiş çevrim yolun yokuş direncini içermiş olur. Bu yöntemin en büyük avantajı, konvansiyonel dinamometrelerde herhangi bir donanım ya da yazılım güncellemesi gerektirmeden uygulanabilecek universal bir metod olmasıdır.

1. INTRODUCTION

Greenhouse effect is a natural phenomenon and can be considered as a regulator, adjusting the temperature of the Earth. Components of the atmosphere that contribute to the greenhouse effect are identified as greenhouse gases (GHG). In the absence of greenhouse effect, the atmospheric mean temperature of the Earth would be about −19 °C rather than the present mean value of about 15 °C (Treut et al., 2007). Therefore, the greenhouse effect resulting from natural sources provides a suitable environment for life in our planet with a balance in production and sink. Before the Industrial Revolution, the amount of greenhouse gases in the atmosphere remained relatively constant for about a thousand years. Since then, the concentration of various greenhouse gases has increased. The amount of carbon dioxide has increased by more than 30% since pre-industrial times and is still increasing at an unprecedented rate of on average 0.4% per year, mainly due to the combustion of fossil fuels (Houghton et al., 2001). The mean temperature of the Earth has increased approximately by 0.8 ^{o}C since 1850s due to excess increase of greenhouse gases, and nearly 0.5 ^{o}C of this increase happened in the last twenty years (Brohan et al., 2006). According to the global industry energy demand, global energy-related CO_2 emissions are expected to rise with an annual growth rate of 1.5%. With this trend over 1000 ppm of CO_2 concentration is estimated by 2030, which is equivalent to an average temperature increase of 6 ^{0}C. (Kojima and Ryan, 2010).

Although internal combustion (IC) engines are not the only sources for GHG production, their contribution is significant. In Turkey, the transport sector accounts for the 18% of CO_2 emissions in energy sector. An increase of 98% in CO_2 emissions is observed between 1990 and 2007. Road transportation contributes to the 83.5% of CO_2 emissions in the transport sector (Soruşbay et al., 2010). Globally, the transport sector accounts for 19% of energy consumption in 2007. According to the projection made between 2007 and 2030, transport sector will contribute for 97% of the increase in world primary oil use (Kojima and Ryan, 2010).

To determine the regional exhaust emissions related to road vehicles, a standard and repeatable method needs to be utilized. The most common method is to simulate the driving conditions on a chassis dynamometer. In order to do that, a driving cycle is required. The driving pattern in a specific region is represented as a driving cycle, which is a vehicle speed-time profile. Driving conditions can then be simulated on a laboratory chassis dynamometer with the aid of this speed-time profile in order to evaluate fuel consumption, exhaust emissions and vehicle emission factors. This method is repeatable and independent of the random characteristics of real world traffic.

Another method is to utilize an on-board measurement system for the real time measurement of exhaust emissions. However, this method is prohibitively expensive and impractical when compared to a measurement on chassis dynamometer. On-board measurements should be repeated over a large period of time to get rid of the random characteristics of real world traffic and seasonal effects.

1.1 Description of Driving Cycles

Vehicle exhaust emissions and emission factors are strongly affected by driving patterns; therefore identifying the driving patterns in a specific region plays a crucial role for the accurate estimation of vehicle emissions. The driving pattern in a specific region is represented as a driving cycle, which is basically a vehicle speed-time profile. Driving conditions can be simulated on a laboratory chassis dynamometer with the aid of this speed-time profile in order to evaluate fuel consumption, exhaust emissions and vehicle emission factors. This method is quite cost effective when compared to direct on-board measurement of exhaust emissions (Dinc et al., 2012). In general, the lengths of driving cycles are in the range of 5 to 60 minutes. Most of the driving cycle durations are between 10 and 30 minutes (Hung et al., 2007). Driving cycles can also be utilized in various areas such as product development, traffic simulation and traffic control.

In this study, a new methodology is proposed to develop a real world driving cycle for the estimation of greenhouse gas (GHG) emissions and a case study is put into practice for the city of İstanbul. Real world statistical data is collected and sequenced into micro-trips. Series of micro-trips are selected with a quasi-random approach until the traveled distance of the driving cycle reaches a predefined limit. Each developed driving cycle is evaluated with respect to the real world test data by using specific comparison criteria and the driving cycle that best represents the driving characteristics of the specific region is chosen as the driving cycle.

1.2 Classification of Driving Cycles

Driving cycles can be classified with two different approach. With the first approach, the driving cycles are classified as legislative and non-legislative. Typical examples of legislative driving cycles are; FTP-75 (Federal Test Procedure) cycle used in the USA, NEDC (New European Driving Cycle) used in Europe and the Japanese 10-15 mode driving cycle. These legislative driving cycles are used for the passenger car emission certification and are imposed by the governments. On the other hand, non-legislative driving cycles such as Athens driving cycle, Hong Kong driving cycle and Edinburgh driving cycle are used for energy conservation and pollution evaluation research (Tzirakisi et al., 2006; Hung et al., 2007; Booth et al., 2001).

With the second approach, the classification of driving cycles is made with respect to the development methodology. First group of cycles is referred as modal or polygonal cycles, which are developed theoretically by combining different driving modes such as constant acceleration, constant deceleration and constant speed. New European Driving Cycle (NEDC) is a typical modal cycle. The second group of cycles is called real-world driving cycles which are developed by using "real-world" actual driving data. FTP-75 and the non-legislative cycles mentioned above are all real-world driving cycles. As opposed to the modal cycles, real-world cycles have more dynamic, non-uniform acceleration and deceleration patterns, which are more realistic. Due to this difference in the pattern of the acceleration and deceleration modes, real-world driving cycles generally lead to different exhaust emissions and fuel consumption when compared to modal driving cycles.

Examples of different types of driving cycles are given in below figures. NEDC is illustrated in Figure 1.1. NEDC is a legislative modal driving cycle. FTP-75, which is a legislative real world driving cycle, is given in Figure 1.2. New York City Cycle (NYCC), which is a non-legislative real world driving cycle is given in Figure 1.3.

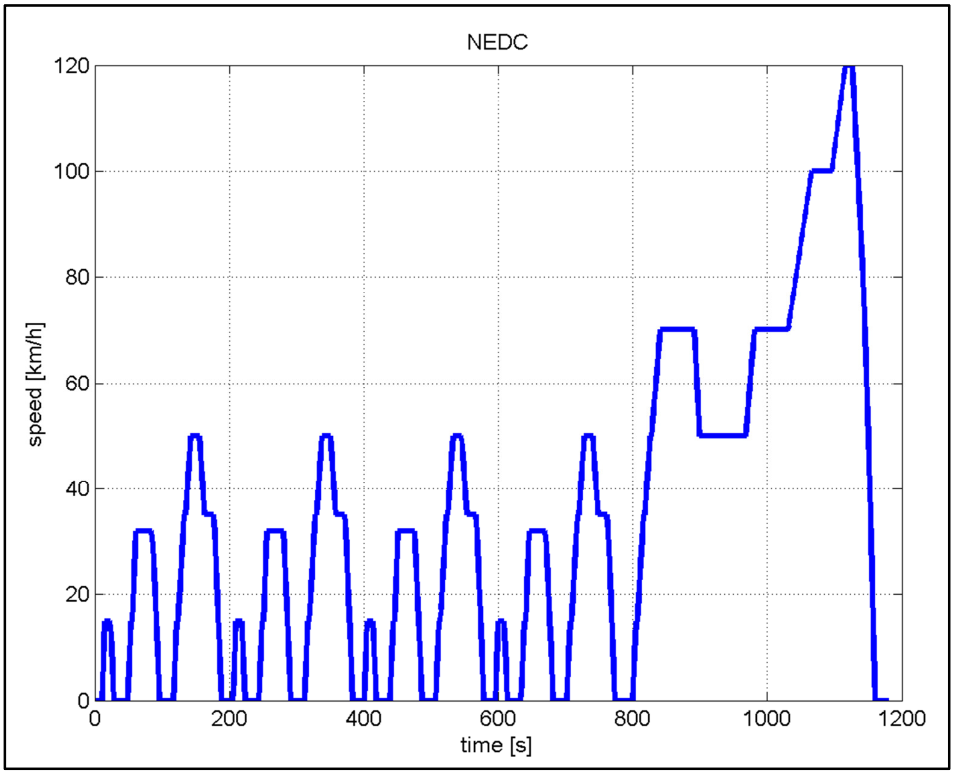

Figure 1.1 : New European Driving Cycle (NEDC).

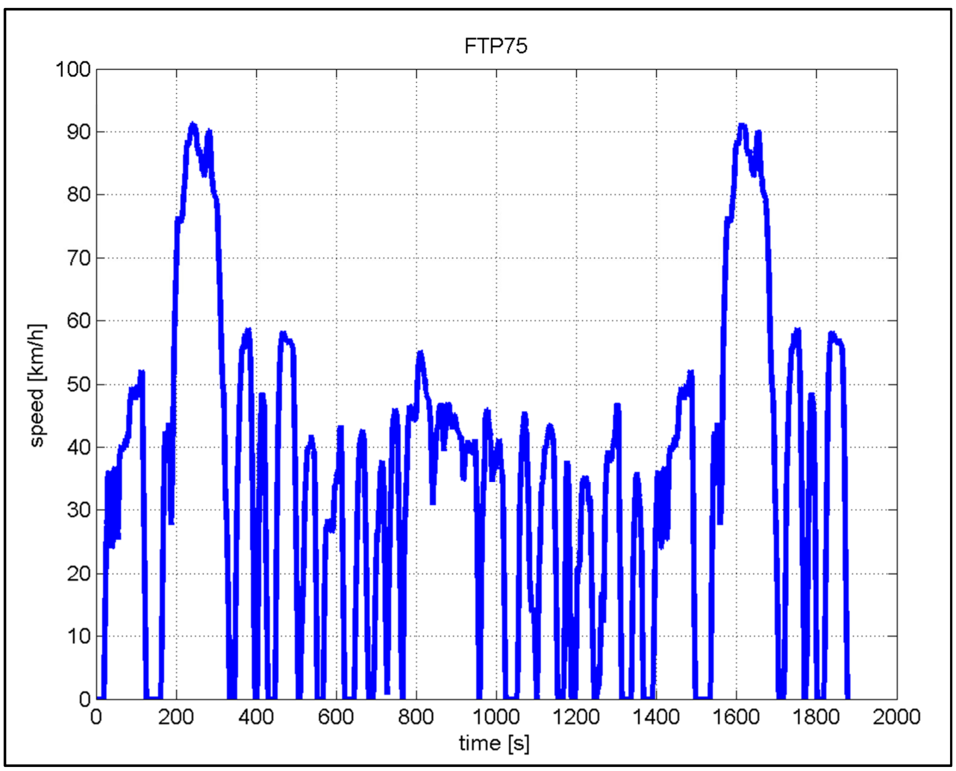

Figure 1.2 : Federal Test Procedure (FPT-75).

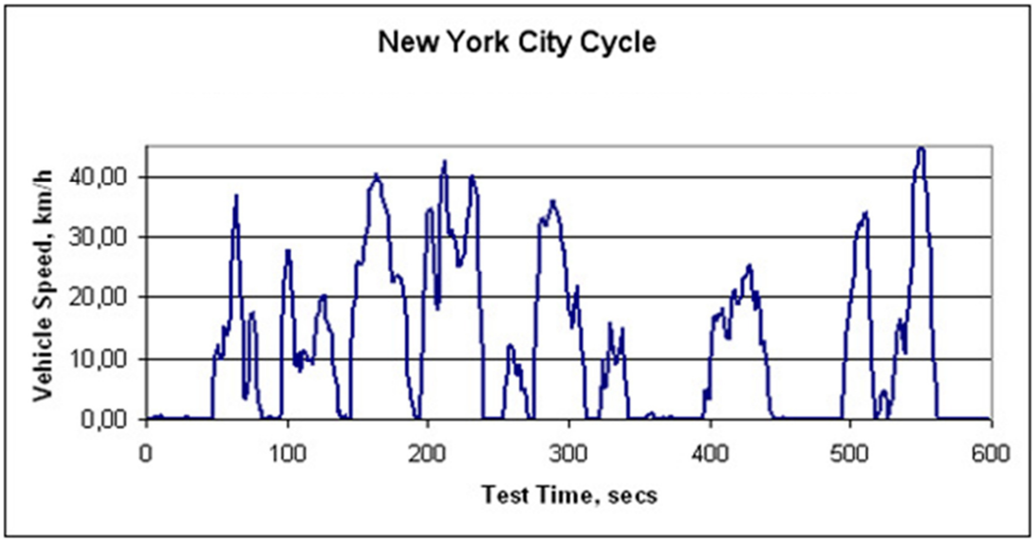

Figure 1.3 : New York City Cycle.

1.3 Literature Review

There are considerable numbers of studies in the literature highlighting the influence of driving conditions on the change in emissions. There is a common understanding that driving patterns are unique for every region and cannot be represented accurately using standard legislative driving cycles (Ergeneman et al., 2010; Charbonnier and Andres, 1993; Cayot, 1995). Furthermore, most of these studies conclude that using such standard legislative cycles underestimate the exhaust emissions for a particular region. Booth et al. (2001) developed a real world driving cycle for the urban area of the city of Edinburgh. When compared with the European ECE cycle, it is reported that the acceleration and deceleration periods of the Edinburgh city cycle occupy 60% of the total cycle. In the European Cycle ECE it is just a third of the total driving cycle period due to the fact that ECE is a modal cycle whereas the Edinburgh city cycle is the result of real traffic measurements. Tzirakis et al. (2006) reported that the European driving cycle is not suitable for the emission estimation for vehicles driven in Athens Basin. Nitrogen oxide emissions obtained with the Athens driving cycle (ADC) increase by up to 300% when compared with the NEDC. Fuel consumption also showed an increase for ADC compared to ECE and NEDC in percentages up to 79% depending on the vehicle. Tong et al. (1999) developed a non-legislative real world driving cycle in the urban area of Hong Kong for the assessment of fuel consumption and exhaust emissions model. It is stated that none of the well-known driving cycles for Europe, Japan and the USA could satisfactorily resemble the Hong Kong driving characteristics. Irregularity of speed, which is defined as the number of acceleration and deceleration changes within one driving period, is shown to be lower with modal cycles relative to the real-world driving cycles. Watson (1995) illustrates that Australian Urban Cycle (AUC), which is a real world driving cycle, leads to emission levels that are considerably higher than the FTP cycle test, about a factor of two for each emission component; HC, CO, and NO_x. Pelkmans and Debal (2006) conclude that NEDC cycle is too smooth to be realistic and vehicle manufacturers only have to focus on limited engine operating zones in order to obtain low emissions for this cycle. According to the results of on road emission measurements in Belgium and Spain, it turned out that a model year 2000 vehicle, which already complied with EURO IV limits, may reach CO and NO_x emissions that may be up to 10 times higher in real traffic compared to the NEDC cycle. Fuel consumption and CO_2 emissions are generally underestimated by 10–20% in the NEDC. Ergeneman et al. (1997) stated that the utilization of European test cycle to predict the total exhaust emissions does not produce accurate results as the average values for vehicle speed and acceleration in a particular region cannot be represented correctly by this approach. To overcome this problem, characteristics of each region have to be determined.

The most common methodology to develop a driving cycle is the "quasi-random" approach, where the cycle is produced by selecting micro-trips from the real world data pool randomly until a pre-defined duration or length is achieved. Additional procedures can be utilized to reduce the number of micro-trips from the original pool to a smaller size, which can still represent the entire base dataset (Kamble et al., 2009; Yu et al., 2008). The representativeness of each cycle produced is evaluated according to some assessment criteria such as average speed, average acceleration, average deceleration, root mean square of acceleration, velocity-acceleration distribution, and positive kinetic energy. The cycle that fits the criteria mentioned best is selected as the final driving cycle. Other approaches for developing a driving cycle are present in the literature. Lin and Niemeier (2002) illustrated a stochastic method for developing a driving cycle. The stochastic method divides a speed trace into modal events (e.g., cruise, idle, acceleration, or deceleration) and describes the sequencing of those events using Markov process theory. The FTP72 and FTP75 cycles are developed by choosing the whole test run data with the most representative speed-time profile based on the idle time, average speed, maximum speed and number of stops per trip (Hung et al., 2007). A compilation of various works to derive real-world driving cycles can be found in (Andre, 2004).

2. METHODOLOGY

In order to create a real world driving cycle, real world driving data needs to be collected in actual traffic. This is a time consuming process and is detailed in this chapter. However, before collecting real world driving data, the most important step is to decide where the driving data is collected.

2.1 Selecting Representative Routes

Selecting representative routes is the first stage in driving cycle construction. This is one of the most significant stages in driving cycle development because this stage directly effects how well the final driving cycle will represent the specific regional driving characteristics at the end. In the succeeding stages, real world driving data will be collected in the selected routes and candidate driving cycles will be constructed from this particular data set. The final stage is to choose the most representative driving cycle amongst the candidate driving cycles. The representativeness of each constructed driving cycle is assessed with respect to the real world data collected in the selected routes. The most representative cycle in terms of specific assessment criteria is chosen as the final driving cycle. Please note that the assessment criteria are used to compare the candidate driving cycles with the real world driving data. How well the real world driving data represents the specific regional driving characteristics is another problem and this directly depends on the process of selecting representative routes. The final driving cycle may represent the real world data very accurately, but it may not represent the regional driving characteristics if the real world data is collected in routes that do not represent the region.

In this thesis, the driving routes are selected with a two-stage process. In the first stage, the commonly used routes of the region are identified as base routes. In the second stage, every selected route is analyzed with respect to the performance parameters of trip duration, road volume/capacity ratio, velocity distribution and total vehicle-distance value with the aid of a regional transportation model. After the completion of this analysis, only the specific parts of the routes, which have similar performance parameters compared to the region, are combined to form the selected routes.

2.1.1 Base routes

Real world driving data is collected in the base routes. The commonly used routes of the region are identified as base routes. Base routes should cover different traffic flow characteristics from congested to free flow urban; and to highway driving characteristics. The base routes only form a starting point for the route selection process. Real world driving data is collected on base routes but only the specific parts, which have similar performance parameters compared to the region, remain to form a driving cycle. Real world driving data is collected in the base routes with a passenger car in real traffic conditions. The required data is vehicle speed as a function of time and altitude. Altitude information is collected in order to estimate instantaneous road grade, which is required to embed the grade effect in the final driving cycle. Real world traffic data is collected in different time periods in the day, also in different days of the week; both in weekdays and weekends.

2.1.2 Selected routes

Not the entire recorded real world driving data is utilized for driving cycle construction. Base routes are analyzed to form the selected routes. Parts of the base routes that do not have similar performance parameters compared to the region are eliminated and are not taken into account for driving cycle generation. This filtering is handled with a regional transportation model. The details of the model can be found in (Gerçek and Çelikoğlu, 2011). The main criterion for the filtering is the volume/capacity ratio, which is a parameter showing the congestion of traffic. After volume/capacity distribution is derived from the transportation model, only the portions of the base routes that have the closest volume/capacity distribution to the average of the specific region are selected for driving cycle generation.

Due to the nature of forming selected routes process, these routes are not continuous but discrete. This is the result of the elimination process. As it is not practical to collect driving data on a discrete route, real world driving data is collected on the continuous base routes, and then only the portions in the selected routes are taken into account for driving cycle generation. The overall process of selecting representative routes is given in Figure 2.1.

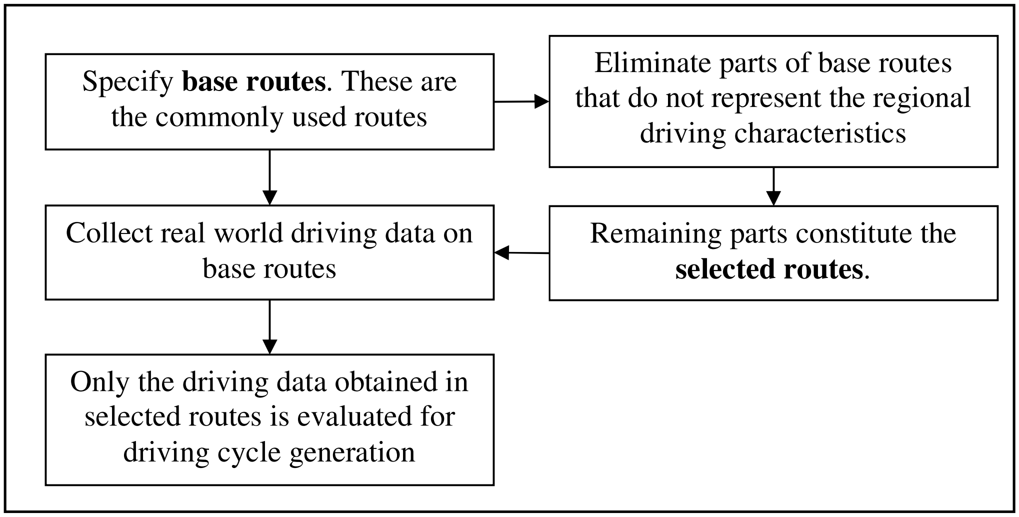

Figure 2.1 : Route Selection Process.

2.2 Segmentation of Driving Data

Real world driving data is formed of velocity data as a function of time with a sampling period of 0.15 seconds. This sampling rate is too small to be used in a quasi-random selection. Thus, the driving data should be represented with larger duration elements.

The segmentation of the driving data is carried out in two stages. The first segmentation works with respect to alternating driving modes; acceleration, constant speed, or deceleration. Prior to segmentation, a moving average approach is utilized to soften the raw driving data. Thus, the different driving modes can be identified more easily. Each segment of the entire test data is defined as a "macro-trip". An example of representing the real world driving data with macro-trips is given in Figure 2.2 for a 60 seconds sample data. As seen in the figure, a new macro-trip is defined every time the driving mode changes. Storing the test data with this approach provides important benefits in the quasi-random selection process in later stages. Macro-trips are the parts that are be used in the quasi-random selection process. The driving cycle is developed with successive random selections of these macro-trips.

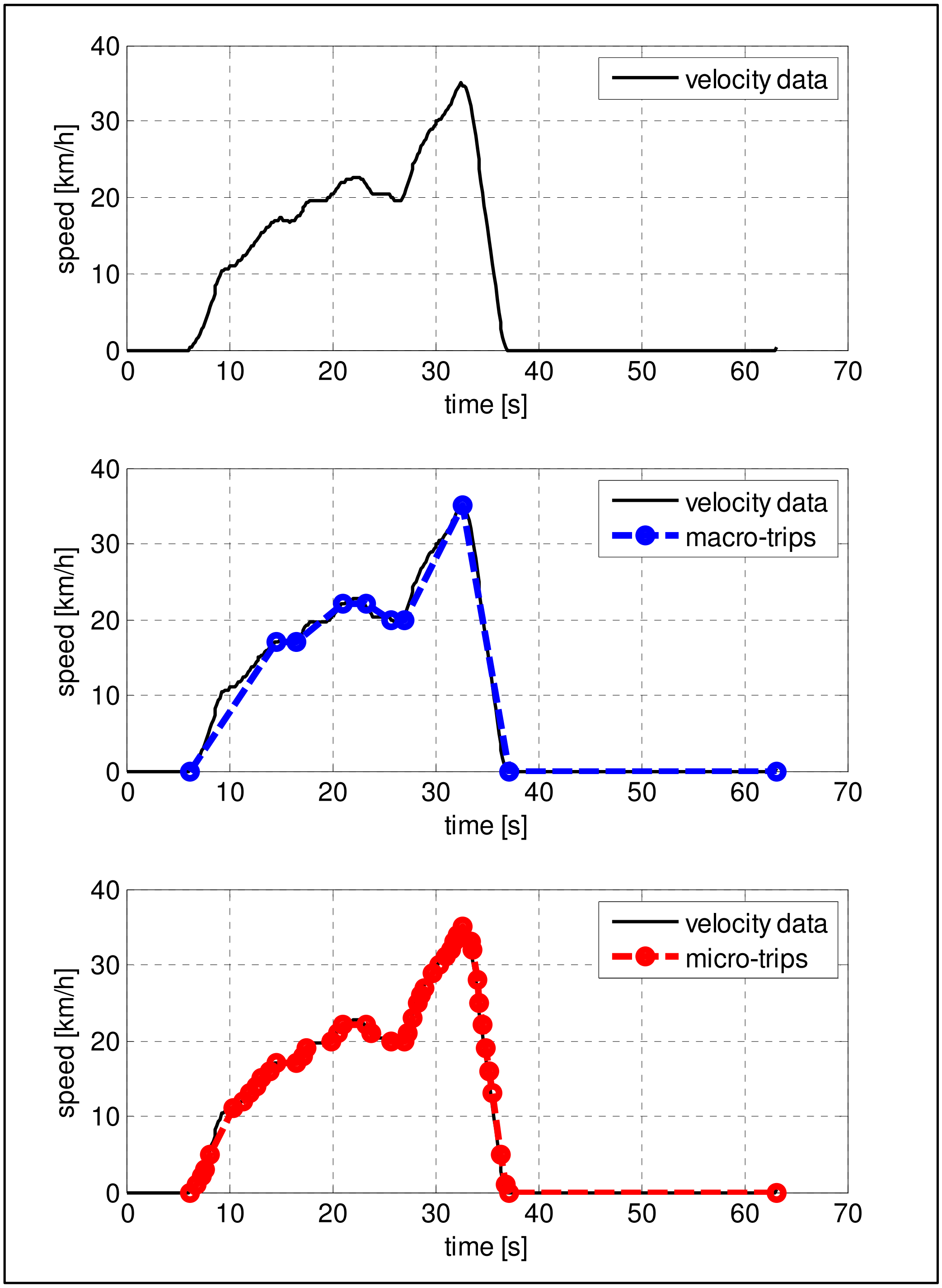

Figure 2.2 : Obtaining macro-trips and micro-trips from real world velocity data.

Even though macro-trips are convenient for quasi-random selection process, they do not possess the fine details needed to represent the driving characteristics accurately. As seen in Figure 2.2, macro-trips do not represent the underlying real world velocity data very accuratelty for some regions. In order to overcome this problem, a second segmentation is carried out. This segmentation is in a similar fashion with the first one, however the obtained elements are shorter. For this reason, these elements are called as micro-trips in the thesis. Micro-trips are finer elements that represent the underlying velocity data very accurately.

Macro and micro-trips are of similar structure. They can be defined with three parameters: initial velocity, final velocity and time. A fourth parameter is added to link the micro-trips with their corresponding macro-trips. This is the cumulative time parameter. After the driving cycle is constructed from the macro-trips, their corresponding micro-trips are found with respect to cumulative time. To give an example, the first five macro-trips shown in Figure 2.2 are given in Table 2.1 in matrix format. The corresponding micro-trips are given in Table 2.2.

Table 2.1 : Macro-trips in matrix format.

Initial Speed [km/h]	Final Speed [km/h]	Time [s]	Cumulative Time [s]
0	0	6.150	6.150
0	17	8.400	14.550
17	17	1.950	16.500
17	22	4.650	21.150
22	22	2.100	23.250

Table 2.2 : Micro-trips in matrix format.

Initial Speed [km/h]	Final Speed [km/h]	Time [s]	Cumulative Time [s]
0	0	6.150	6.150
0	1	0.750	6.900
1	2	0.450	7.350
2	3	0.300	7.650
3	11	2.850	10.500
11	12	0.900	11.400
12	13	0.600	12.000
13	14	0.600	12.600
14	15	0.525	13.125
15	16	0.750	13.875
16	17	0.675	14.550
17	17	1.950	16.500
17	18	0.600	17.100
18	19	0.450	17.550
19	20	2.400	19.950
20	21	0.600	20.550
21	22	0.600	21.150
22	22	2.100	23.250

As seen in these tables, constant speed phases are the same in macro/micro-trip representation. Only the macro-trips with acceleration or deceleration are represented with finer micro-trips.

2.3 Setting the Constraints for the Driving Cycle

Prior to the initialization of quasi-random selection process, some parameters that define the characteristics of the driving cycle need to be defined. These are cycle length, number of idle phases and idling percentage.

2.3.1 Cycle length

With increasing cycle length, the representativeness of the driving cycle increases. At the very limit, if cycle length is chosen to be equal to the route length, then the route is represented completely with the driving cycle. However, this is not practical since it is very hard to conduct such a long simulation on a laboratory chassis dynamometer. A short cycle time is always desirable. Hence, there is trade-off between representativeness and applicability of a driving cycle under laboratory conditions. Considering this trade-off, the cycle length is determined iteratively. After a reasonable number of driving cycles are generated for different cycle lengths, the optimum length is chosen considering both representativeness and applicability. The details of this process are given in the following sections of this chapter.

2.3.2 Number of idle phases

Number of idle phases is defined as the number of times that the vehicle comes to a full stop. This is determined in parallel with cycle length. For instance, if the cycle length is determined to be 1/10 of the route length, then the number of idle phases is also set as 1/10 of the number of idle phases observed in this route.

2.3.3 Idling percentage

Idling percentage is determined in a similar fashion to number of idle phases. This is the ratio of time spent with idling to the overall duration of the cycle.

With respect to the constraints mentioned above, the initial pattern of the driving cycle is determined as seen in Figure 2.3. The bold lines represent the travelling units while the thinner lines represent the times where the vehicle is at full stop; idle mode.

The number of idle phases is n. $unit_1$, $unit_2$,...,$unit_n$ are the travelled distances for each travelling unit and are determined randomly for each driving cycle generated; however, the constraint that their sum is equal to the pre-determined cycle length should always be satisfied. Exact satisfaction of this constraint may not be satisfied for every travelling unit due to the nature of quasi-random selection process. The deviation for each travelling unit is stored as residual distance and compensated in the following travelling units. $idle_1$, $idle_2$,...,$idle_{n+1}$ are the idling phases. Their total duration can be altered even after the driving cycle is constructed, such that idling percentage of the region is approximated closely.

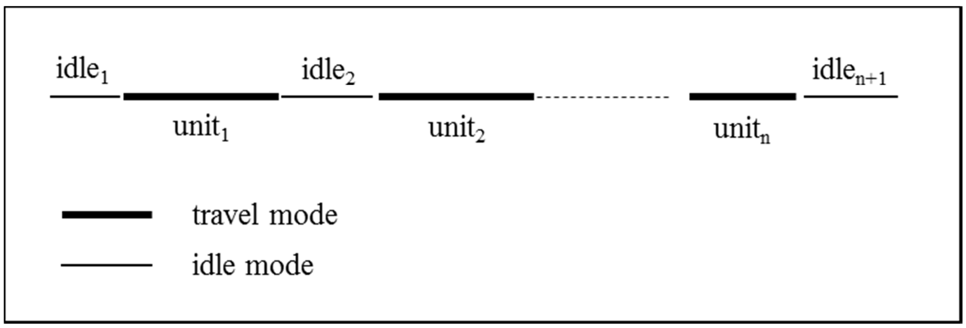

Figure 2.3 : Driving cycle pattern.

2.4 Quasi-Random Selection Process

After the segmentation of the driving data into macro-trips and the identification of driving cycle constraints, the quasi-random selection process is initiated. This process is constituted of consecutive addition of macro-trips. An example can be seen in Figure 2.4. For each addition, the driving cycle development algorithm searches for macro-trips whose initial speeds are equal to the final speed of the latest added macro-trip. The selection process is continued until the pre-defined length of the travelling unit is reached. That is one of the reasons why the selection process is named as quasi-random, rather than just random. It is not a fully random process since it can be interfered to satisfy driving cycle constraints. An example for this interference can be given when the travelling unit distance is reached and an idle mode should be placed in the following selection. In this case, the algorithm imposes to choose a macro-trip with the final speed of zero. If such a macro-trip cannot be found in the macro-trip database, the algorithm imposes to choose macro-trips with negative acceleration so that cycle ends up with lower velocities after each macro-trip selection. By this way, the chance to find a macro-trip with final speed of zero is increased with every selection.

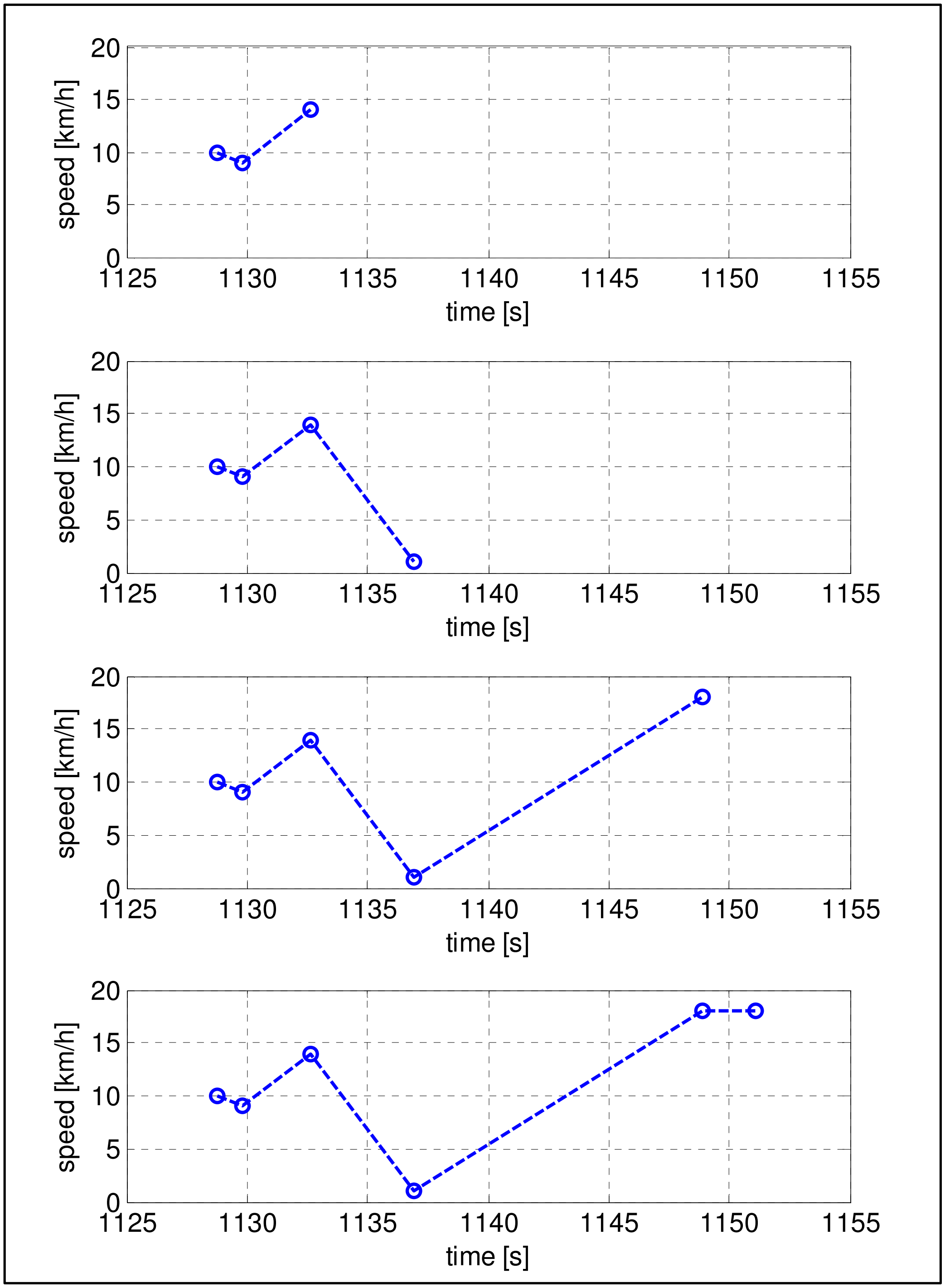

Figure 2.4 : Consecutive addition of macro-trips.

Switching to an idling mode is not the only exception when the random selection process is interfered. In the course of driving cycle construction, some critical parameters specifying the driving characteristics are monitored. If there is a significant deviation for a parameter, the selection process may be interfered. For instance, at a specific time of driving cycle construction, if it is found that the average velocity of the overall cycle falls behind the average velocity of the region, the algorithm imposes to choose macro-trips with positive acceleration.

2.5 Choosing the Best Cycle

Every driving cycle constructed according to the process defined in the previous chapters is called a candidate cycle. A constructed driving cycle is stored in memory as a candidate cycle only if it has less than 5% error related to all assessment criteria and it represents the regional driving characteristics more accurately than all previous candidate driving cycles. After a considerable number of iterations are completed, the latest candidate driving cycle; hence the most representative one, is chosen as the final driving cycle. The most critical issue here is the method to quantify the representativeness of a candidate driving cycle. The parameters that are used to evaluate the representativeness of a candidate driving cycle are called assessment criteria. The assessment criteria utilized in this thesis are:

- Percentage of idling
- Average speed
- Average acceleration
- Average deceleration
- Average positive specific power
- Average negative specific power

2.5.1 Assessment criteria

2.5.1.1 Percentage of idling

Percentage of idling is also defined as a driving cycle constraint prior to driving cycle development. This parameter can be approximately very accurately in the final driving cycle, since it was already defined as a constraint.

2.5.1.2 Average speed

As the name suggests, this is the average speed of the driving cycle. The average speed of each candidate driving cycle is compared with the average velocity of the region. The average speed of each macro-trip is calculated as shown in (2.1). $v_{1,i}$ is the initial speed of each macro-trip whereas the $v_{2,i}$ is the final speed of the macro-trip. The first index of the speed parameters identifies if the speed value is the initial or final speed of the macro-trip. The second index; *i*, is used to indicate that the calculated parameter is valid for the specific ith macro-trip.

$$v_{avg,i} = \frac{v_{1,i} + v_{2,i}}{2} \tag{2.1}$$

The average speed of the whole driving cycle; $v_{avg,cycle}$, is calculated using a time-weighted average approach (2.2). t_i is the time duration of individual macro-trips.

$$v_{avg,cycle} = \frac{\sum v_{avg,i} \times t_i}{\sum t_i} \tag{2.2}$$

The calculation approach of average speed is also given in tabular format in Table 2.3. The first four columns show the macro-trip details, and the fifth column shows the average speed calculation. Please note that average speed is not embedded into macro-trip matrix.

Table 2.3 : Calculation of average speed for individual macro-trips.

v_1	v_2	t	t_c	v_{avg}
Initial Speed [km/h]	Final Speed [km/h]	Time [s]	Cumulative Time [s]	Average Speed [km/h]
0	0	6.150	6.150	0.0
0	17	8.400	14.550	8.5
17	17	1.950	16.500	17.0
17	22	4.650	21.150	19.5
22	22	2.100	23.250	22.0

2.5.1.3 Average acceleration

Average acceleration of the cycle, and of the region, is calculated considering only the macro-trips having a positive acceleration. The average acceleration of each macro-trip is calculated as shown in (2.3). Speeds are divided by 3.6 for conversion to m/s.

$$a_i^{+} = \left(\frac{v_{2,i} - v_{1,i}}{t_i}\right) \times \frac{1}{3.6} \qquad \textbf{(2.3)}$$

The average acceleration of the whole driving cycle; a^{+}_{cycle}, is calculated using a time-weighted average approach (2.4).

$$a_{cycle}^{+} = \frac{\sum a_i^{+} \times t_i}{\sum t_i} \qquad \textbf{(2.4)}$$

2.5.1.4 Average deceleration

Average deceleration of the cycle, and of the region, is calculated considering only the macro-trips having a negative acceleration. The average deceleration of each macro-trip is calculated as shown in (2.5). Speeds are divided by 3.6 for conversion to m/s. Please note that average deceleration is always negative, since $v_{2,i} < v_{1,i}$ for macro-trips with decelerating motion.

$$a_i^{-} = \left(\frac{v_{2,i} - v_{1,i}}{t_i}\right) \times \frac{1}{3.6} \qquad \textbf{(2.5)}$$

The average deceleration of the whole driving cycle; a^{-}_{cycle}, is calculated using a time-weighted average approach (2.6).

$$a_{cycle}^{-} = \frac{\sum a_i^{-} \times t_i}{\sum t_i} \qquad \textbf{(2.6)}$$

2.5.1.5 Average positive specific power

It has been stated in the literature review section that speed acceleration distribution is one of the most significant criteria to assess the representativeness of a driving cycle. However, since this parameter is a 3-D distribution, it is hard to associate the speed acceleration distribution of the driving cycle with the region and calculate an error parameter indicating the deviation. For simplicity, a new parameter is defined in this thesis, in order to supersede speed acceleration distribution. This is average specific power. It is obtained by the multiplication of speed and acceleration for each macro-trip (2.7). As in acceleration and deceleration calculations, positive and negative specific powers are calculated separately.

$$P_i^+ = a_i^+ \times v_i \qquad \textbf{(2.7)}$$

The average positive specific power of the whole driving cycle; P^+_{cycle}, is calculated using a time-weighted average approach (2.8).

$$P_{cycle}^+ = \frac{\sum P_i^+ \times t_i}{\sum t_i} \qquad \textbf{(2.8)}$$

2.5.1.6 Average negative specific power

Average negative specific power is calculated by the multiplication of speed and acceleration for each decelerating macro-trip (2.9). As in acceleration and deceleration calculations, positive and negative specific powers are calculated separately.

$$P_i^- = a_i^- \times v_i \qquad \textbf{(2.9)}$$

The average positive specific power of the whole driving cycle; P^+_{cycle}, is calculated using a time-weighted average approach (2.10).

$$P_{cycle}^- = \frac{\sum P_i^- \times t_i}{\sum t_i} \qquad \textbf{(2.10)}$$

2.5.2 Assessment of driving cycle error

After a candidate cycle is constructed, the assessment criteria are calculated for that driving cycle. Every assessment criteria is evaluated with respect to the region. The regional values for the assessment criteria are calculated prior to driving cycle calculation. The error calculation for average specific power is given below (2.11). E_{P+} is the error related to be average positive specific power. P^+_{region} is the average positive specific power of the region and is calculated based on the entire real world driving data.

$$E_{P+} = \left| \frac{P_{cycle}^+ - P_{region}^+}{P_{region}^+} \right| \qquad \textbf{(2.11)}$$

The error calculations for the other assessment criteria are carried out with similar approach. If the calculated error values for all assessment criteria are less than 5%, the cycle is considered as a candidate cycle and it is stored in memory. After a considerable number of iterations are completed, the candidate driving cycle having the lowest error for the average of positive and negative specific power is selected as the final driving cycle (2.12). Special attention is paid to specific power terms since they have a higher significance compared to other assessment criteria.

$$E_{cycle} = \frac{\left|E_{P^+}\right| + \left|E_{P^-}\right|}{2} \quad \textbf{(2.12)}$$

The summary of the driving cycle construction algorithm is given in Figure 2.5.

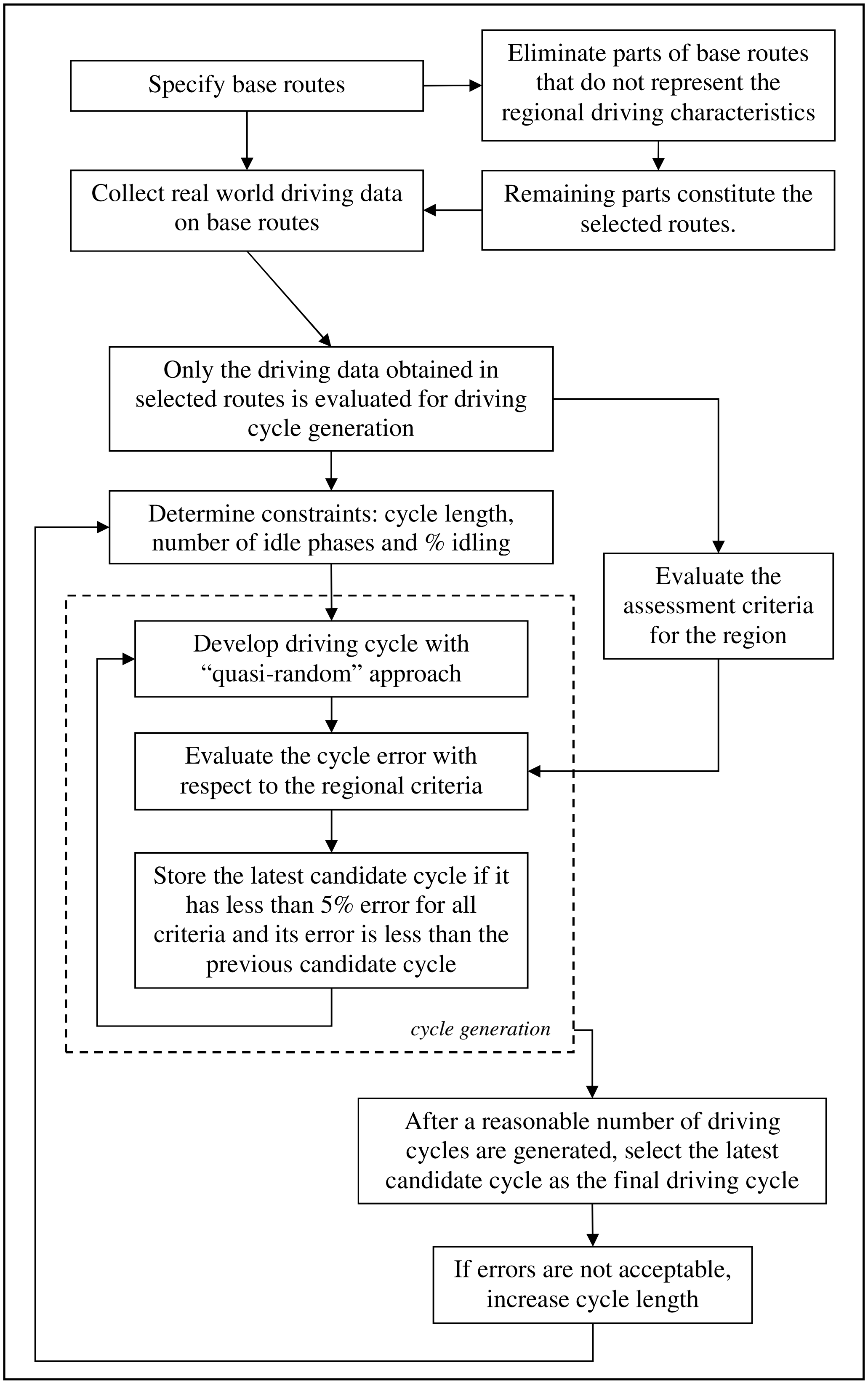

Figure 2.5 : Driving cycle construction algorithm.

3. CASE STUDY: İSTANBUL DRIVING CYCLE (IDC)

In this chapter, a real world driving cycle generated for İstanbul based on the methodology presented in previous chapter is described. In order to create a real world driving cycle, real world driving data needs to be collected in actual traffic. However, before collecting real world driving data, the most important step is to decide where the driving data is collected.

According to the driving cycle construction methodology in this thesis, the driving routes are selected with a two-stage process. In the first stage, the commonly used routes of the region are identified as base routes. In the second stage, parts of the base routes that do not have similar performance parameters compared to the region are eliminated and are not taken into account for driving cycle generation. This filtering is handled with a regional transportation model.

3.1 Base Routes

The commonly used routes of the region are identified as base routes. The base routes identified for the city of İstanbul are as follows:

- Route#1: Maslak - Göztepe Route: Maslak (İTÜ Campus) - Zincirlikuyu - Bosphorus Bridge - Altunizade - Göztepe
- Route#2: Maslak- Kozyatağı Route: Maslak (İTÜ Campus) - 4.Levent - Fatih Sultan Mehmet Bridge - TEM Highway - Kozyatağı
- Route#3: Maslak - Bakırköy Route: Maslak (İTÜ Campus) - Zincirlikuyu - Merter - Bakırköy
- Route#4: Historical Peninsula Route: Haliç

The base routes can be seen in Figure 3.1.

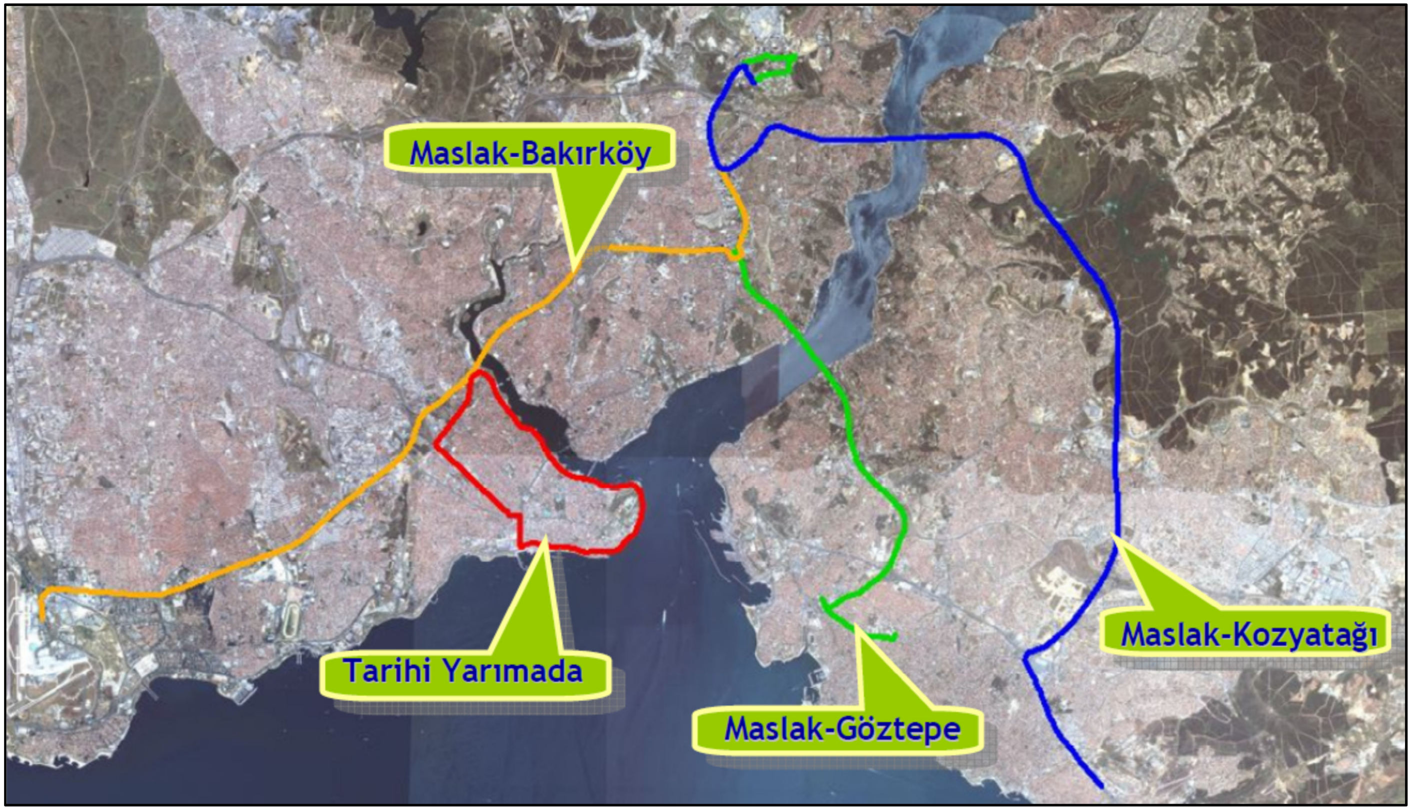

Figure 3.1 : Base routes for İstanbul.

The base routes cover different traffic flow characteristics from congested to free flow urban; to highway driving characteristics. The two bridges connecting Europe and Asia, which are Bosphorus Bridge and Fatih Sultan Mehmet Bridge, are included in the first and second routes respectively. The main arterial roads that connect the bridges to the urban divided multi-lane highways are D100 expressway and TEM freeway. These roads are included in the first three routes. Multi-lane highways are connected to urban roads, which are included in each main route. The fourth route, Historical Peninsula (Haliç) is made up of all urban roads representing congested traffic conditions. Please note that the base routes only form a starting point for the route selection process. Real world driving data is collected on base routes but only the specific parts, which have similar performance parameters compared to the region, remain to form a driving cycle.

After the base routes are determined, the data acquisition process can be initiated. Real world driving data is collected in the base routes with Renault Megane passenger car, equipped with a data logger. The data logger is interfaced with the electronic control module (ECM) of the vehicle and records vehicle speed as a function of time. The vehicle is also equipped with a global positioning system (GPS) device, which records altitude. Altitude information is collected in order to estimate instantaneous road grade, which is required to embed the grade effect in the final driving cycle. The specifications of the car are given in Table 3.1.

Table 3.1 : Specifications of the data acquisition vehicle.

Vehicle Type	Passenger Car
Brand and model	Renault Megane 2004
Engine	1.9 dCi, 4 cylinders
Max. power	90 PS @ 4000 rpm
Max. torque	230 Nm @ 2000 rpm
Weight	1345 kg
Wheelbase	2625 mm
Total length	4209 mm
Track width	1518 mm
Total width	1777 mm
Height	1457 mm
Final drive ratio	4.07
Data acquisition	Speed: ECM Altitude: GPS

Photos of the car and data acquisition equipment are given in Figure 3.2 and Figure 3.3. respectively. Real world traffic data is collected in morning and evening peak traffic conditions as well as off-peak conditions; both in weekdays and weekends. The main motivation of the driver is to follow the overall flow of the traffic as close as possible. For instance, in highways middle lane is used instead of the left hand lane.

Figure 3.2 : A photo of the data acquisition car.

Figure 3.3 : A photo from the interior of data acquisition car.

3.2 Selected Routes

Not the entire recorded real world driving data in İstanbul is utilized for driving cycle construction. Base routes of İstanbul are analyzed with the regional transportation model of İstanbul to form the selected routes. The details of the model can be found in (Gerçek and Çelikoğlu, 2011). The main criterion for the filtering is the volume/capacity ratio distribution of İstanbul, which is a parameter showing the congestion of traffic. After volume/capacity distribution is derived from the İstanbul transportation model, only the portions of the base routes of İstanbul that have the closest volume/capacity distribution to the average of İstanbul are selected for driving cycle generation. The instantaneous traffic flow characteristics on the base routes are estimated with the aid of the data obtained from the remote traffic monitoring system (RTMS) sensors. It is paid attention that all of the base routes are in the span of RTMS. The locations of RTMS sensors on the base routes can be seen in Figure 3.4.

The remaining portions of the base routes; in other words the selected routes for İstanbul can be seen in Figure 3.5.

3.3 Construction of İstanbul Driving Cycle

Individual driving cycles are generated for each route seperately. Then, they are combined to generate the İstanbul Driving Cycle. The weighting factor of each route is determined according to its own duration in the overall region.

3.3.1 Construction of individual cycles

In this section, the focus is the driving cycle construction for the individual routes. For every route, the constraints of cycle length, number of idle phases and idling percentage are defined before driving cycle construction. Then, the regional criteria of average speed, average acceleration, average deceleration, average positive specific power and average negative specific power are defined. These regional characteristics are used to assess the representativeness of the constructed driving cycles for every route. The individual driving cycles are Maslak-Göztepe, Maslak-Kozyatağı, Maslak-Bakırköy and the Historical Peninsula (Haliç) cycles.

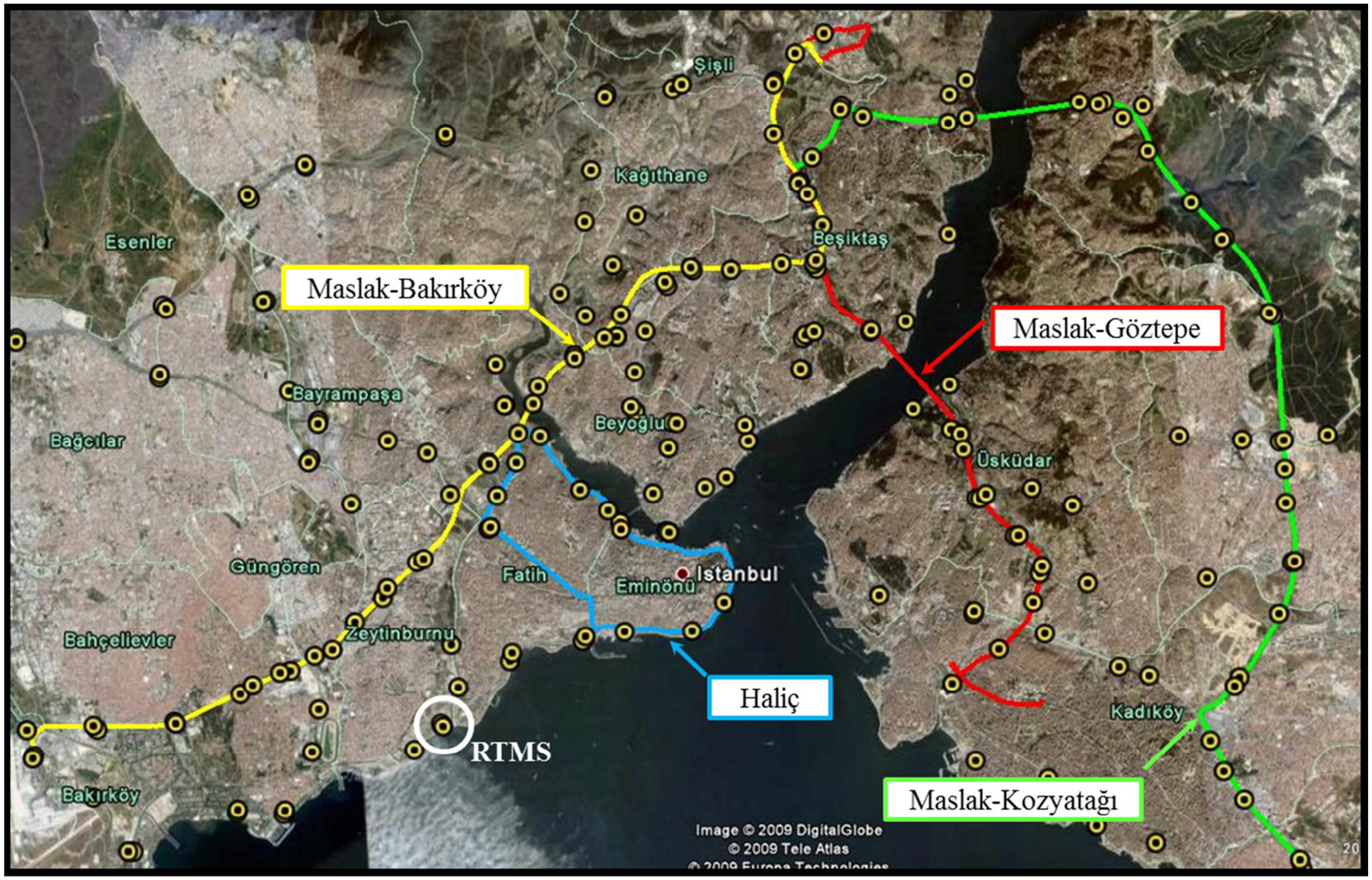

Figure 3.4 : Locations of remote traffic monitoring system sensors.

Figure 3.5 : Selected routes for İstanbul.

3.3.1.1 Maslak-Göztepe cycle

The assessment criteria calculated for the Maslak-Göztepe route, and for the generated driving cycle are given in Table 3.2. The values given in the route row represent the region. The percentage errors of the cycle, which are calculated with respect to the region, are also given in the last row of the table. As seen from the error values, every assessment criterion is represented with less than 5% error. Therefore, it can be concluded that the regional driving characteristics are represented very accurately.

Table 3.2 : Error analysis of the Maslak-Göztepe cycle.

	Duration	Idling	v_{avg}	a^{+}_{route}	a^{-}_{route}	P^{+}_{route}	P^{-}_{route}
	s	*%*	*km/h*	*m/s^2*	*m/s^2*	*m^2/s^3*	*m^2/s^3*
Route	1465	10.00	26.31	0.498	-0.517	3.936	-4.173
Cycle	202	10.10	27.18	0.477	-0.503	3.871	-4.135
% Error	-	1.1	3.3	4.1	2.7	1.6	0.9

The constructed driving cycle for the Maslak-Göztepe route is given in Figure 3.6.

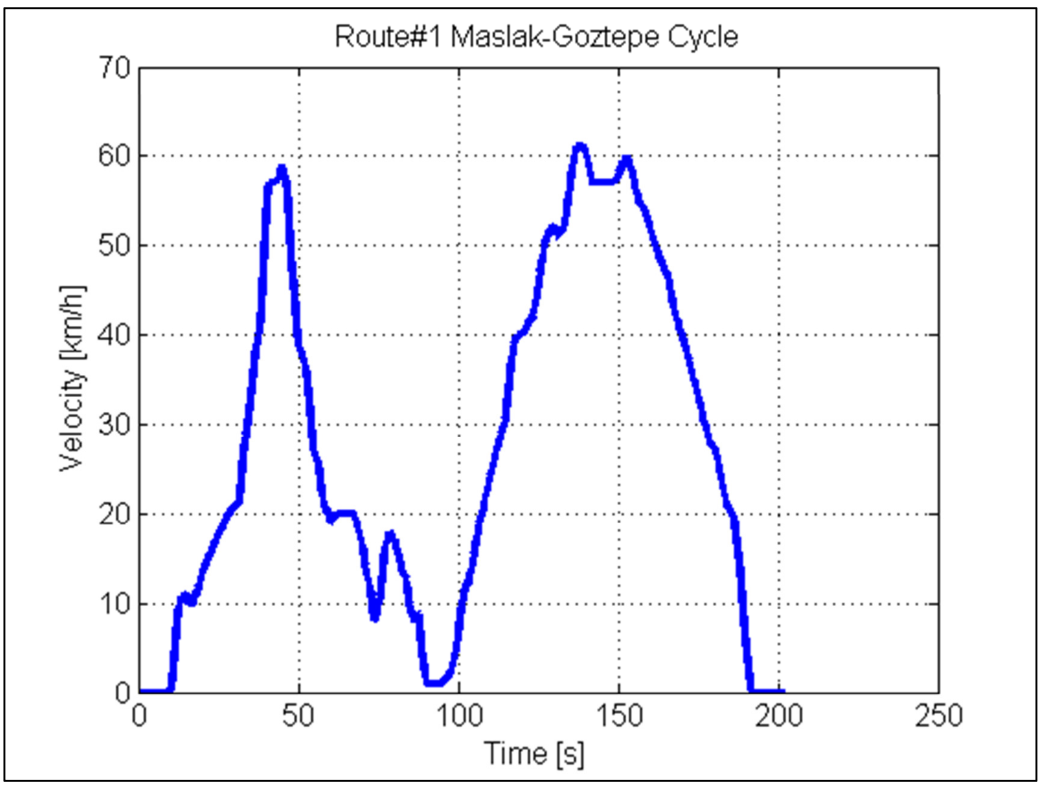

Figure 3.6 : Maslak-Göztepe driving cycle.

3.3.1.2 Maslak-Kozyatağı cycle

The assessment criteria calculated for the Maslak-Kozyatağı route, and for the generated driving cycle are given in Table 3.3. The values given in the route row represent the region. The percentage errors of the cycle, which are calculated with respect to the region, are also given in the last row of the table. As seen from the error values, every assessment criterion is represented with less than 5% error. Therefore, it can be concluded that the regional driving characteristics are represented very accurately.

Table 3.3 : Error analysis of the Maslak-Kozyatağı cycle.

	Duration	Idling	v_{avg}	a^{+}_{route}	a^{-}_{route}	P^{+}_{route}	P^{-}_{route}
	s	*%*	*km/h*	m/s^2	m/s^2	m^2/s^3	m^2/s^3
Route	1049	5.55	36.84	0.518	-0.535	5.022	-5.312
Cycle	129	5.71	38.28	0.511	-0.540	5.109	-5.456
% Error	-	2.8	3.9	1.2	0.9	1.7	2.7

The constructed driving cycle for the Maslak-Kozyatağı route is given in Figure 3.7.

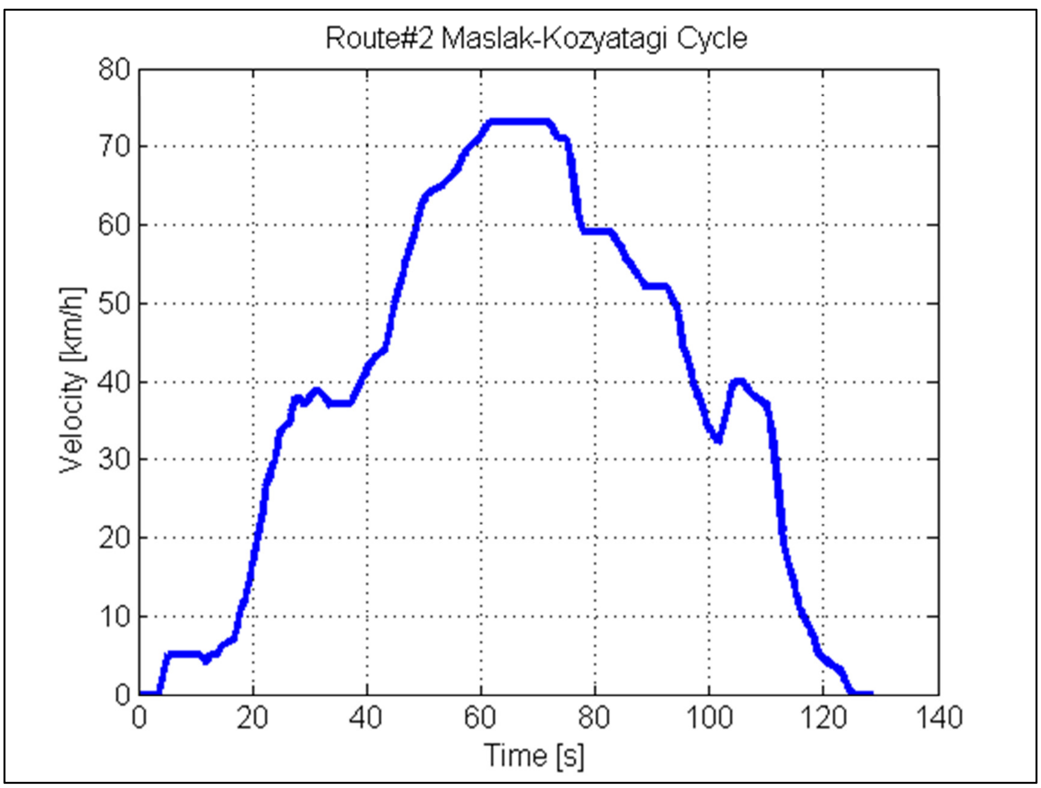

Figure 3.7 : Maslak-Kozyatağı driving cycle.

3.3.1.3 Maslak-Bakırköy cycle

The assessment criteria calculated for the Maslak-Bakırköy route, and for the generated driving cycle are given in Table 3.4. The values given in the route row represent the region. The percentage errors of the cycle, which are calculated with respect to the region, are also given in the last row of the table. As seen from the error values, every assessment criterion is represented with less than 5% error. Therefore, it can be concluded that the regional driving characteristics are represented very accurately.

Table 3.4 : Error analysis of the Maslak-Bakırköy cycle.

	Duration	Idling	v_{avg}	a^{+}_{route}	a^{-}_{route}	P^{+}_{route}	P^{-}_{route}
	s	*%*	*km/h*	m/s^2	m/s^2	m^2/s^3	m^2/s^3
Route	3213	6.48	31.51	0.469	-0.479	4.094	-4.232
Cycle	419	6.47	31.46	0.447	-0.466	4.108	-4.331
% Error	-	0.1	0.2	4.7	2.6	0.3	2.4

The constructed driving cycle for the Maslak-Bakırköy route is given in Figure 3.8.

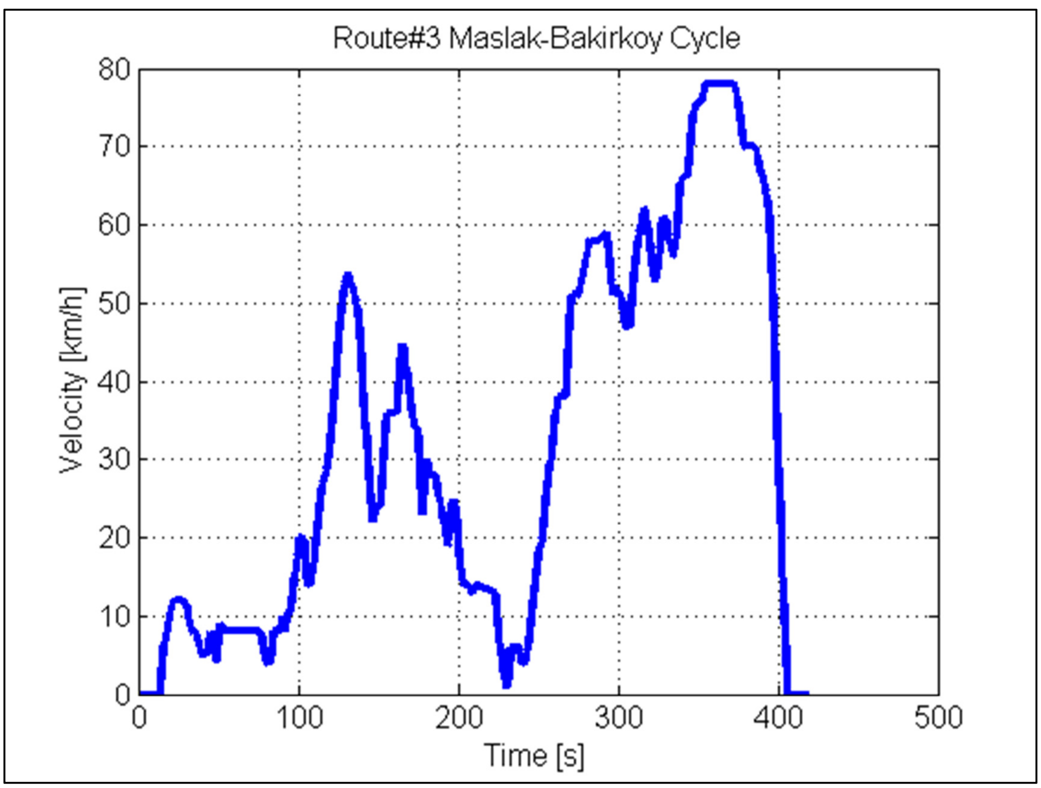

Figure 3.8 : Maslak-Bakırköy driving cycle.

3.3.1.4 Historical Peninsula (Haliç) cycle

The assessment criteria calculated for the Historical Peninsula route, and for the generated driving cycle are given in Table 3.5. The values given in the route row represent the region. The percentage errors of the cycle, which are calculated with respect to the region, are also given in the last row of the table. As seen from the error values, every assessment criterion is represented with less than 5% error. Therefore, it can be concluded that the regional driving characteristics are represented very accurately.

Table 3.5 : Error analysis of the Historical Peninsula cycle.

	Duration	Idling	v_{avg}	a^+_{route}	a^-_{route}	P^+_{route}	P^-_{route}
	s	*%*	*km/h*	m/s^2	m/s^2	m^2/s^3	m^2/s^3
Route	1903	17.82	28.10	0.616	-0.620	5.216	-5.345
Cycle	254	17.92	29.11	0.599	-0.608	5.166	-5.331
% Error	-	0.5	3.6	2.9	1.9	1.0	0.3

The constructed driving cycle for the Historical Peninsula route is given in Figure 3.9.

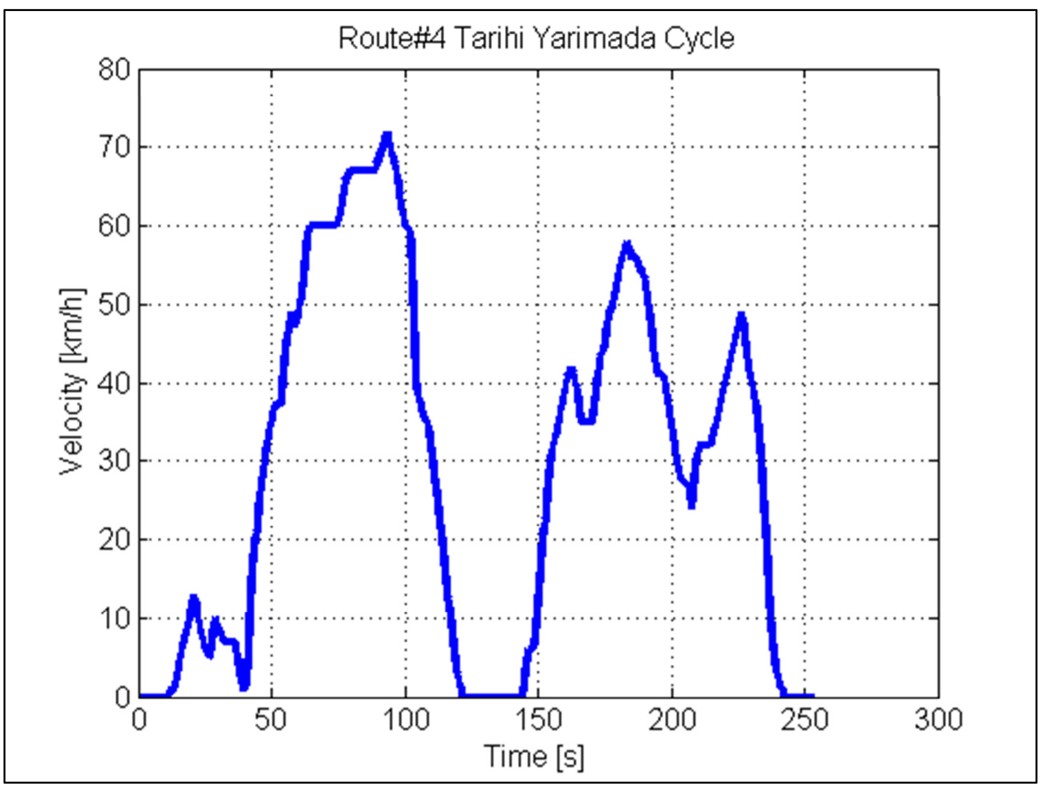

Figure 3.9 : Historical Peninsula driving cycle.

3.3.2 Construction of İstanbul Driving Cycle

All of the individual cycles are created with the same scaling factor. In other words; the average duration or time of the routes are scaled down with the same factor. Therefore, without any additional operation, these individual driving cycles can be combined to form the İstanbul Driving Cycle (IDC).

The basic properties of IDC are given in Table 3.6. Please note that the representativeness of a driving cycle is quantified with the assessment criteria. Therefore, the assessment criteria need to be calculated for IDC. The assessment criteria of the region and of IDC are given in Table 3.7. The values given in the route row represent the region. The percentage errors of the cycle, which are calculated with respect to the region, are also given in the last row of the table. As seen from the error values, every assessment criterion is represented with less than 5% error. Error is less than 1% for average specific power terms. Therefore, it can be concluded that the regional driving characteristics are represented very accurately.

Table 3.6 : Basic properties of İstanbul Driving Cycle.

	Duration	Distance	Max. Speed
	s	*km*	*km/h*
IDC	1003	8.61	78.0

Table 3.7 : Assessment criteria and error analysis of İstanbul Driving Cycle.

	Idling	v_{avg}	a^+_{route}	a^-_{route}	P^+_{route}	P^-_{route}
	%	*km/h*	m/s^2	m/s^2	m^2/s^3	m^2/s^3
Route	9.86	30.40	0.518	-0.529	4.471	-4.646
Cycle	10.00	30.88	0.500	-0.519	4.456	-4.689
% Error	1.4	1.6	3.5	1.9	0.3	0.9

The constructed driving cycle for the city of İstanbul is given in Figure 3.10.

3.3.3 Comparison of IDC with FTP-75 and NEDC

In this section, İstanbul Driving Cycle (IDC) is compared with legislative cycles of FTP-75 and NEDC in terms of basic cycle properties, fuel economy and exhaust emissions. The comparison of basic properties is given in Table 3.8. It is seen that IDC has the lowest average speed when compared with FTP-75 and NEDC. This is due to the congested traffic condition in İstanbul. In terms of maximum speed, NEDC cycle has the highest speed.

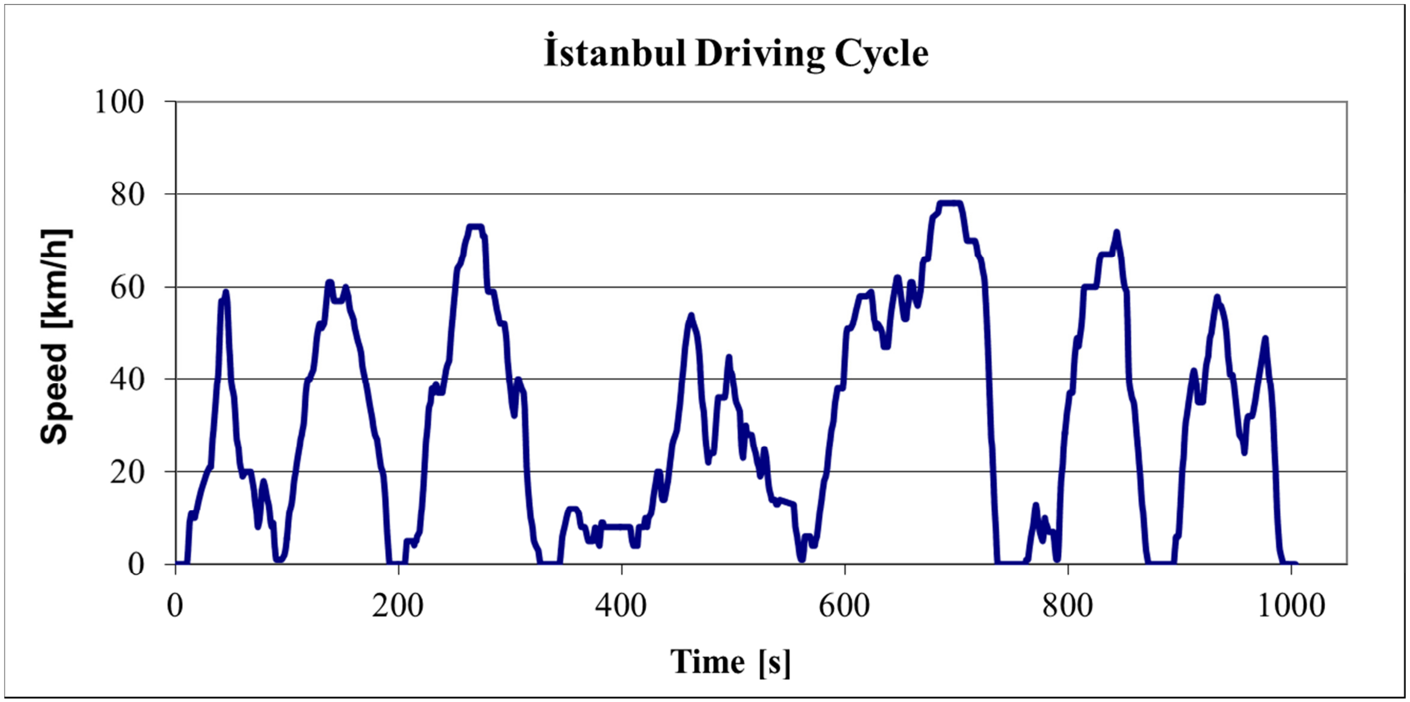

Figure 3.10 : İstanbul Driving Cycle.

Table 3.8 : Comparison of basic cycle properties.

	Duration	Distance	Max. Speed	Avg. Speed
	s	*km*	*km/h*	*km/h*
IDC	1003	8.61	78.0	30.9
NEDC	1180	11.01	120.0	33.6
FTP-75	1877	17.87	91.2	34.1

To compare İstanbul Driving Cycle (IDC) with legislative cycles of FTP-75 and NEDC in terms of fuel economy and exhaust emissions, dynamometer tests are carried out with thirty passenger cars with spark ignition engine of different model year and emission control technology (Öztürk, 2010). The model years and emission control technologies of the test vehicles are selected to reflect the passenger car fleet with spark ignition engine in Turkey. A total number of 30 vehicles are tested in chassis dynamometer. The sample size for every emission control technology is given in Table 3.9.

Table 3.9 : Number of test vehicles for different emission control technologies.

Emission Control Technology	Number of Test Vehicles
Uncontrolled (UC)	10
R15.04	9
EURO I	3
EURO III	5
EURO IV	3

The CO_2 emissions and fuel consumption values obtained with three different driving cycles are given in Table 3.10. Please note that these are the average values for the sample of cars tested in every emission control technology group. The emission certification in Turkey is put into use after 1994. The vehicles having model year before 1994 are named as uncontrolled (UC). These vehicles have low combustion efficiency. For some vehicles in this group, leakages are observed in the exhaust system and these are not included in the measurements. Consequently, the highest fuel consumption values are obtained for UC group.

As seen in Table 3.10, the fuel consumption values obtained with IDC are higher compared to FTP75 and NEDC for every emission control technology. Considering FTP75 cycle, the fuel consumption values obtained with IDC are 15 to 30% higher for different emissions technologies. Considering NEDC cycle, the fuel consumption values obtained with IDC are 4 to 12% higher for different emission control technologies. The results show that, the regional driving characteristics of İstanbul; hence, the exhaust emissions cannot be represented accurately with legislative cycles of FTP75 and NEDC.

Considering the CO_2 emissions level of the three cycles, the above relationship is not so clear. Especially for vehicles with older emission control technologies, higher CO_2 emission levels are obtained for NEDC compared to IDC. This is due to the fact that for vehicles with older technologies, fuel cannot be oxidized efficiently; and therefore converted to CO_2. This argument can be verified by checking the HC emissions of these vehicles in Table 3.11. HC emissions indicate the amount of unburnt fuel and it is seen that for vehicles with older emission control technologies HC emissions are very high. As the emission control technology progresses, the trend of CO_2 emissions change become aligned with the fuel consumption trend. Considering EURO IV emission control technology, the highest CO_2 emissions are obtained with IDC; parallel with the fuel consumption trend. For a visual comparison, fuel consumption and CO_2 emissions values obtained with three different driving cycles are shown with bar charts in Figure 3.11 and Figure 3.12 respectively.

Table 3.10 : Comparison of CO_2 emissions and fuel consumptions.

	FTP75		NEDC		IDC	
Emission Control Technology	CO_2	Fuel Cons.	CO_2	Fuel Cons.	CO_2	Fuel Cons.
-	*g/km*	*l/100km*	*g/km*	*l/100km*	*g/km*	*l/100km*
UC	149.5	7.9	169.1	8.6	157.4	9.6
R15.04	139.2	6.8	166.1	7.8	165.9	8.1
EURO I	134.8	6.0	169.5	7.5	170.8	7.8
EURO III	133.3	5.9	155.4	6.9	159.6	7.2
EURO IV	144.9	6.2	153.6	6.5	164.7	7.1

The HC, CO and NO_x emissions values obtained with three different driving cycles are given in Table 3.11. As seen in the Table 3.11, the exhaust emissions values obtained with IDC are quite different from the values obtained with FTP75 and NEDC. CO and HC emissions obtained with IDC are higher than the legislative cycles of FTP75 and NEDC for every emission control technology group. Considering NEDC, higher NO_x emissions are obtained compared to IDC except for

EURO IV vehicles. The possible root cause of this is the higher speed region at end of NEDC.

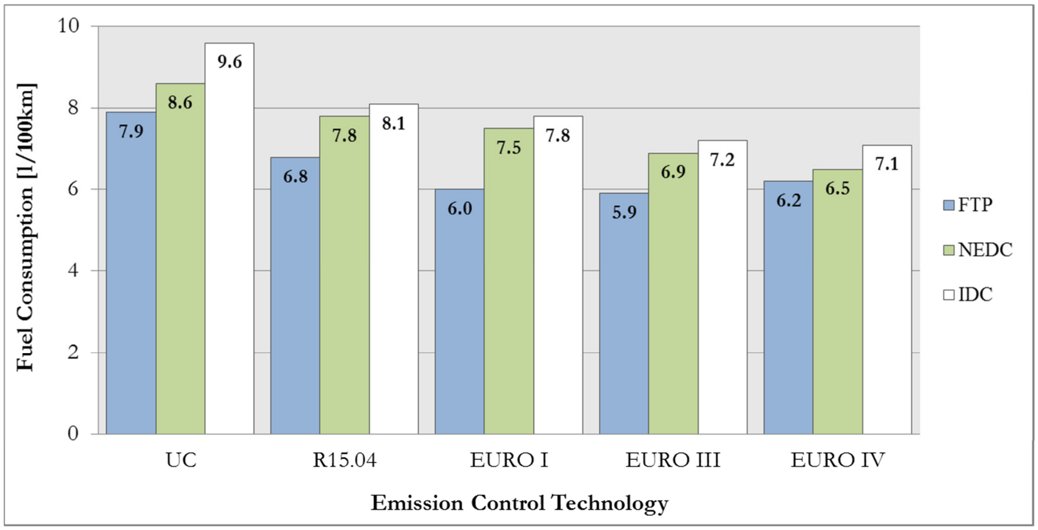

Figure 3.11 : Comparison of fuel consumptions for IDC, NEDC and FTP cycles.

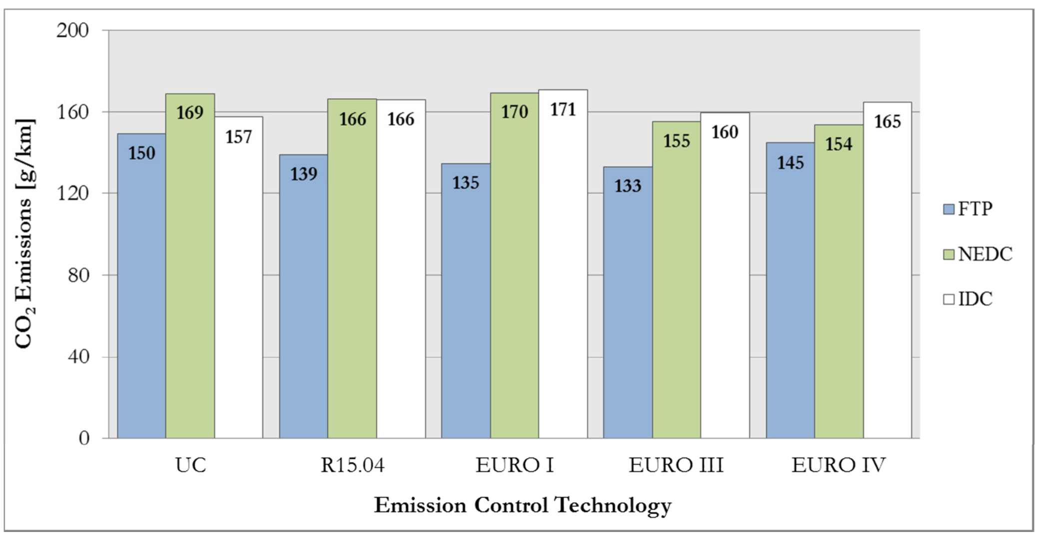

Figure 3.12 : Comparison of CO_2 emissions for IDC, NEDC and FTP cycles.

All of these results show that, the regional driving characteristics of İstanbul; hence, the fuel consumption and exhaust emissions, cannot be represented accurately with legislative cycles of FTP75 and NEDC. For the accurate estimation of vehicle emissions in a specific region, the unique driving patterns of this region need to be identified in the form of a real world driving cycle.

Table 3.11 : Comparison of HC, CO and NO_x emissions.

	FTP75			NEDC			IDC		
	HC	CO	NO_x	HC	CO	NO_x	HC	CO	NO_x
		g/km			*g/km*			*g/km*	
UC	2.99	16.50	1.15	2.19	17.77	1.33	4.14	36.47	0.85
R15.04	1.40	9.31	1.06	1.13	10.24	1.16	1.53	13.91	1.02
EURO I	0.60	2.36	0.59	0.65	3.39	0.72	0.92	7.07	0.66
EURO III	0.54	2.63	0.30	0.52	3.74	0.40	0.72	5.88	0.37
EURO IV	0.05	0.43	0.03	0.05	0.52	0.05	0.16	1.37	0.08

For a visual comparison, HC, CO and NO_x emissions and fuel consumption values obtained with three different driving cycles are shown with bar charts in Figure 3.13, Figure 3.14 and Figure 3.15 respectively.

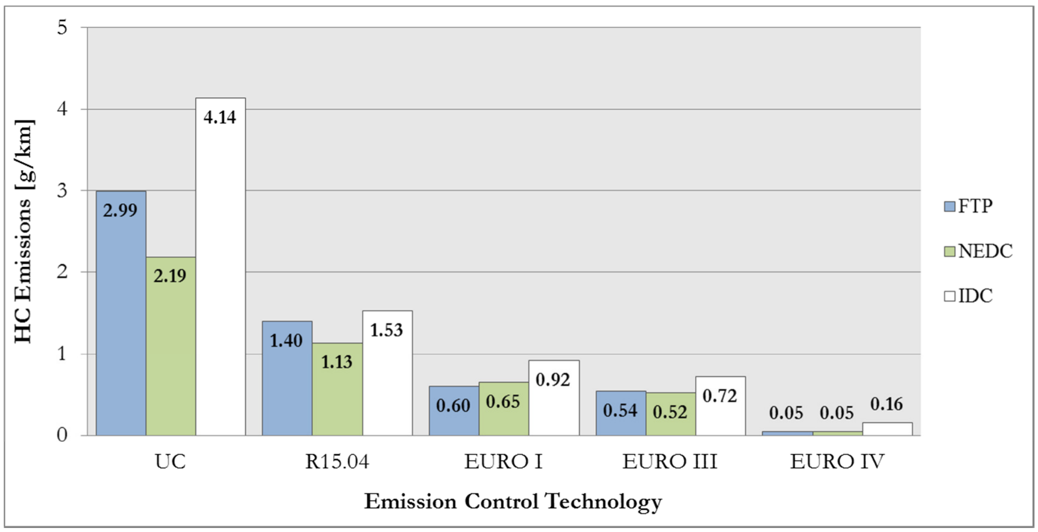

Figure 3.13 : Comparison of HC emissions for IDC, NEDC and FTP cycles.

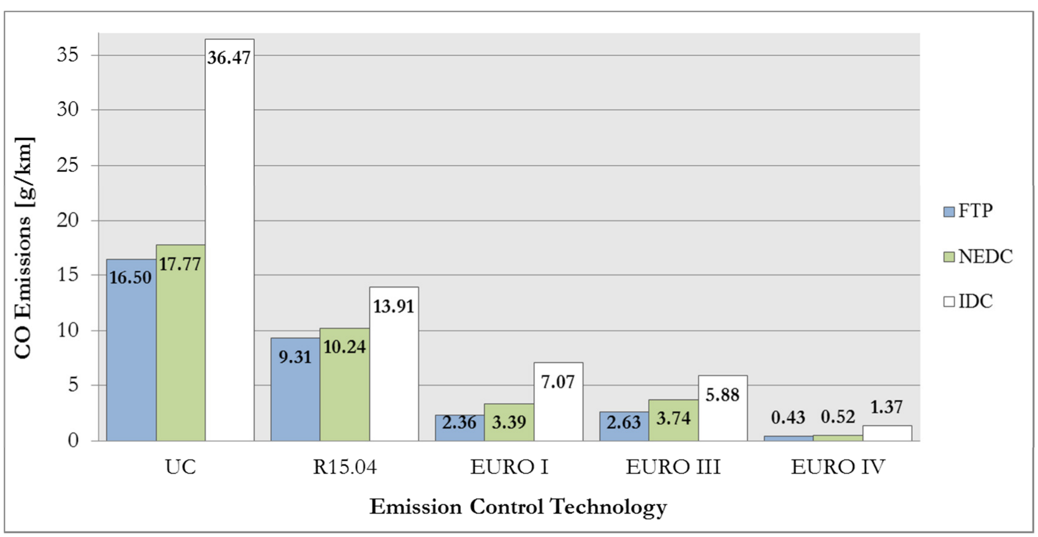

Figure 3.14 : Comparison of CO emissions for IDC, NEDC and FTP cycles.

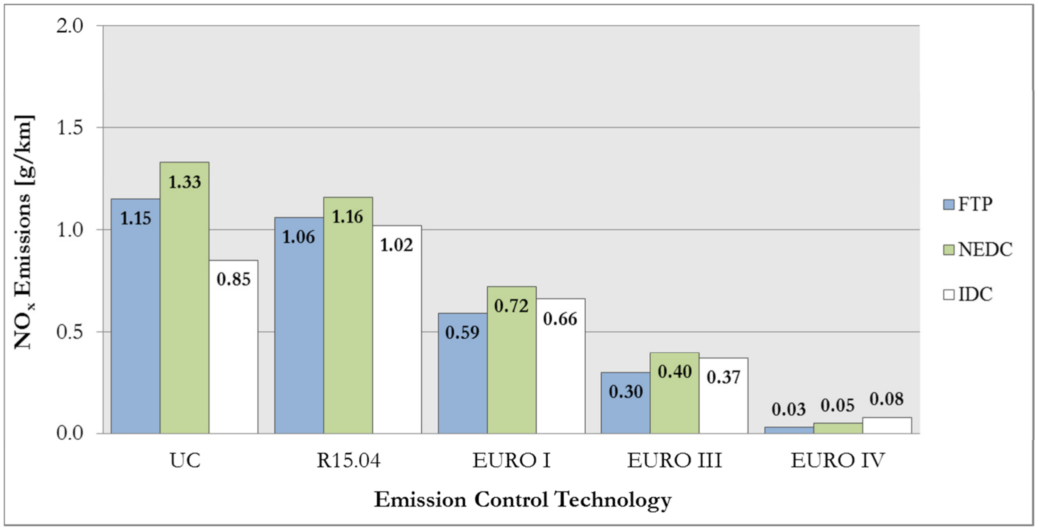

Figure 3.15 : Comparison of NO_x emissions for IDC, NEDC and FTP cycles.

4. EMBEDDING ROAD GRADE EFFECT INTO A DRIVING CYCLE

4.1 Motivation of Embedding Grade Effect

The total road work equation for a real world driving condition is given in (4.1). W_{roll} is the rolling resistance work, W_{aero} is the aerodynamic work, W_{acc} is the work due to the acceleration/deceleration of the vehicle, and finally W_{grade} is the grade work.

$$\sum W_{road} = W_{roll} + W_{aero} + W_{acc} + W_{grade} \tag{4.1}$$

W_{roll}; rolling resistance work is calculated as shown in (4.2). m is the vehicle mass, g is gravitational acceleration, f_r is the rolling resistance coefficient and x is the distance covered. f_r is assumed as 0.015 in the calculations, which is the typical value given for passenger cars and concrete road (Gillespie, 1992).

$$W_{roll} = m \times g \times f_r \times x \tag{4.2}$$

W_{aero}; aerodynamic work is calculated as shown in (4.3). ρ is the air density, C_d is the aerodynamic drag coefficient, A_f is the frontal area of the vehicle. v_{avg} is the average speed of the considered micro-trip. Average speed of the micro-trip is simply the average of initial and final velocities.

$$W_{aero} = \frac{1}{2} \rho \times C_d \times A_f \times v_{avg}^2 \times x \tag{4.3}$$

W_{acc}; acceleration work is calculated as shown in (4.4). a is the vehicle acceleration or deceleration.

$$W_{acc} = m \times a \times x \tag{4.4}$$

W_{grade}; grade work is calculated as shown in (4.5). $\varnothing$ is the road grade and is approximated with the small angle assumption (4.6).

$$W_{acc} = m \times g \times \phi \quad \textbf{(4.5)}$$

Ø is the road grade and is approximated with the small angle assumption (4.6).

$$\phi = \sin(\phi) = \tan(\phi) \quad \textbf{(4.6)}$$

Real world driving data is collected in actual traffic conditions, where there is altering road grade. A driving cycle is generated from this real world driving data and it is simulated on a chassis dynamometer. In this situation, the effect of road grade is not included. The total work equation for a simulation on a chassis dynamometer is given in equation (4.7).

$$\sum W_{dyno} = W_{roll} + W_{aero} + W_{acc} \quad \textbf{(4.7)}$$

The difference between the total road work and total dynamometer work gives the residual work that cannot be represented in a typical chassis dynamometer test (4.8).

$$\Delta W = \sum W_{road} - \sum W_{dyno} = W_{grade} \quad \textbf{(4.8)}$$

Due to the W_{grade} term, the driving characteristics of the region, especially the topology characteristics, cannot be represented on a flat chassis dynamometer testing facility. Consequently, the regional exhaust emission factors cannot be estimated accurately. This is the main motivation to embed the grade effect into a real world driving cycle.

4.2 Methodology of Embedding Grade Effect

There can be two different solution proposals for the above problem. The first one is to add or subtract the extra force related to the grade work term into the chassis dynamometer with hardware or software update. This is possible since the grade of every micro-trip in the driving cycle is known. However, this requires additional software or hardware update and is not practical to apply in conventional chassis dynamometer testing facility.

The second proposal, which is the adopted methodology in this thesis, is to embed the residual work term arising from the grade effect into the driving cycle by modifying its trip properties. This is a universal solution to the problem presented above since it can be utilized in a conventional dynamometer setting without any update or additional procedure.

The modification of the driving cycle trip properties can be carried out in two different ways. The trip properties can be modified in terms of velocity or time. Modifying the velocities of micro-trips is not preferred due to two main reasons. The first reason is that modifying the velocity of the micro-trips instead of time alters the average velocity of the micro-trip, which deteriorates the original regional driving characteristics. Hence, it would effect the exhaust emission characteristics of the micro-trip. The second reason is that the micro-trips in a driving cycle are coupled sequentially. If the initial or final velocity of an individual micro-trip is altered, that also effects the preceding or the next micro-trip, which requires a complex iterative modification. Therefore, modification of micro-trip velocity approach cannot be applied to an already generated driving cycle. This method must be applied to the whole micro-trips in the original pool before cycle generation algorithm is initiated; therefore, it is computationally expensive. More significant than computation time, since velocities of the micro-trips are altered to compensate for the grade work, the quasi-random selection algorithm can fail to find an appropriate micro-trip during driving cycle construction. When these disadvantages of modifying micro-trip velocities are taken into consideration, it is decided to modify micro-trips only with respect to time.

For the modified case, the total dynamometer work equation can be stated as in equation (4.9).

$$\sum W_{dyno}^{*} = W_{roll}^{*} + W_{aero}^{*} + W_{acc} \qquad \textbf{(4.9)}$$

Please note that W_{acc} is not altered for the modified case. Although the acceleration of the micro-trip is altered when the time duration of the micro-trip is changed, the distance covered is altered with the same ratio, but with opposite sign. Therefore, W_{acc} is constant in this modification. Since the initial and final velocities of the micro-trip are not modified, however trip duration is changed, the grade work is completely embedded into rolling and aerodynamic work. For instance, a positive grade effect can be embedded into a micro-trip by increasing its trip duration; therefore, increasing its rolling and aerodynamic road work such that the grade work is compensated. The new rolling and aerodynamic work is named as W^{*}_{roll} and W^{*}_{aero} instead of W_{roll} and W_{aero} respectively. The * script refers to the modification.

The main motivation is to minimize the difference between the total road work and total dynamometer work. The calculation of the difference is given equation (4.10).

$$\Delta W^{*} = \sum W_{road} - \sum W^{*}_{dyno} = W_{roll} + W_{aero} + W_{grade} - \left(W^{*}_{roll} + W^{*}_{aero}\right) \quad \textbf{(4.10)}$$

The grade work representation in the driving cycle is indicated with the ΔW^{*} term. Please note that rolling and aerodynamic work terms are always positive, whereas; grade work term can be positive or negative depending on road grade.

The method of embedding the grade effect into the micro-trip is deep dived in this section for different driving scenarios of uphill and downhill driving conditions.

4.2.1 Collecting and smoothing altitude data

In order to embed grade effect into a driving cycle, altitude data needs to be collected during real world data acquisition. This can easily be satisfied with a GPS device. However, GPS data acquisition can easily be disturbed by high buildings and clouds during real world data acquisition. Therefore, a pre-processing stage needs to be carried out before the altitude data can be used for cycle generation. The correction or smoothing of the GPS data is beyond the scope of this thesis. Nevertheless, practical solutions utilized in this study are mentioned in this chapter very briefly.

First of all, a curve fitting approach can be used to estimate the road trajectory. Since the interval of curve fitting is quite large in a typical real world driving test, spline fitting is preferred. Spline fitting can be summarized as piecewise polynomial fitting. For conventional polynomial fitting, the degree of the approximating polynomial can be unacceptably large for a real world driving trip. In case of spline, this large driving trip is subdivided into smaller intervals and a relatively low degree polynomial can provide a good approximation to the road trajectory on each interval.

Curve fitting may not be adequate to obtain a continuous and robust road grade due to the deficiency of the GPS data. An additional filtering may be utilized in the driving cycle generation phase. Micro-trips having very unrealistic acceleration values can be marked and not taken into consideration for driving cycle construction.

4.2.2 Modifying micro-trips according to work equation

The modification of micro-trips according to work equation is handled for two different scenarios; uphill and downhill driving conditions. For uphill driving condition, the total work of the micro-trip needs to be increased to compensate for the additional grade work. Therefore, micro-trip duration is increased. For downhill driving condition, the total work of the micro-trip needs to be decreased to compensate for the negative grade work. Therefore, micro-trip duration is decreased. The details for these two scenarios are discussed in the following chapters.

4.2.2.1 Uphill Micro-Trips

For uphill micro-trips, there is a positive grade work. In other words, the vehicle needs to produce more work to overcome this grade work. In order to represent this work, the duration of the micro-trip needs to be increased. An example is given in Figure 4.1.

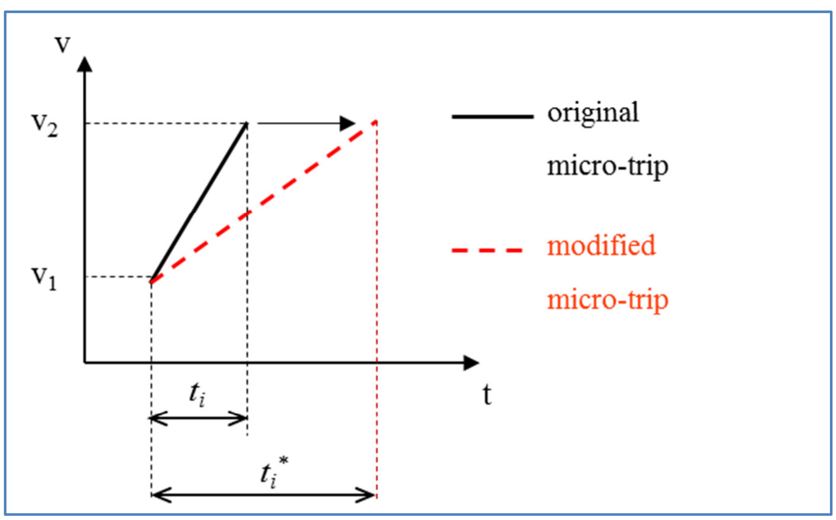

Figure 4.1 : Modification of an uphill micro-trip.

Since only time is modified in this methodology, v_{avg} is the same for the original and modified micro-trip. Therefore, the incremental work term which compensates the road grade work comes from the t_i^*/t_i term, which is called the modification ratio. For uphill driving conditions, t_i^*/t_i term is always greater than one. The rolling and aerodynamic work terms increase at en equal rate with the modification ratio. This is an expected outcome; since v_{avg} is the same for the original and modified micro-trip, the only variable that can alter the rolling resistance work and aerodynamic work is the distance covered, and the increase of the distance covered for the modified micro-trip is proportional to the modification ratio. When the modification ratio is plugged into equation (4.10), the simplified form of this equation comes as shown in equation (4.11). Please note that W_{grade} is always positive since the micro-trip is for an uphill driving condition.

$$\Delta W^* = W_{roll} + W_{aero} + W_{grade} - (W_{roll} + W_{aero})\frac{t_i^*}{t_i} \qquad \textbf{(4.11)}$$

The simplified version of this equation is given in (4.12).

$$\Delta W^* = (W_{roll} + W_{aero})\left(1 - \frac{t_i^*}{t_i}\right) + W_{grade} \qquad \textbf{(4.12)}$$

The key issue to embed the grade work is to choose the appropriate modification ratio t_i^*/t_i so that ΔW^* term, which is the work difference between road and dynamometer, is minimized. For instance; if the modification ratio is chosen as one, which means that the original micro-trip is not modified, ΔW^* term becomes equal to grade work; which brings us to the starting point where the grade work is not represented. For higher modification ratios, the grade work is compensated and the work difference between road and dynamometer conditions is minimized.

The only obstacle of this method for uphill driving conditions is that, for some micro-trips the modification ratio may need to be very high. Especially for low speed driving conditions; where W_{roll} and W_{aero} are relatively low and for very steep uphill conditions; where the W_{grade} is relatively high, it may be needed to choose a very high modification ratio to compensate for the grade effect. For such conditions, modification ratio is limited to a pre-determined value such that the modified micro-trip does not end up to be too much extended. Obviously, when the modification ratio is limited, the grade work for this specific micro-trip is not fully compensated.

4.2.2.2 Downhill Micro-Trips

For downhill case, the modification is just the opposite of uphill conditions. There is a negative grade work. In other words, the vehicle needs to produce less work to make use of this negative grade work. In order to represent this case, the duration of the micro-trip needs to be decreased. An example is given in Figure 4.2.

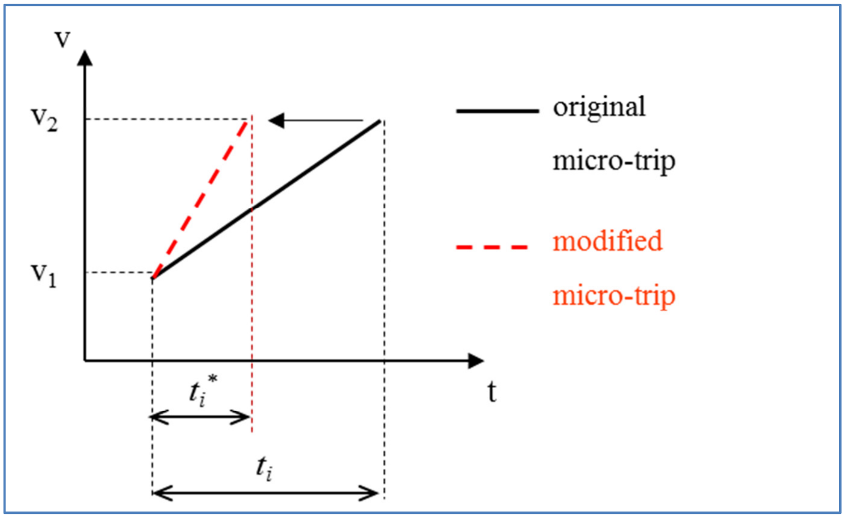

Figure 4.2 : Modification of a downhill micro-trip.

In contrast with the uphill case, for downhill case the rolling and aerodynamic work terms are decreased. In other words; for downhill driving conditions, t_i^*/t_i term is always smaller than one. Micro-trip duration is shortened which decreases the rolling resistance and aerodynamic work terms. The equations for the uphill case are also valid for the downhill case. Obviously, the W_{grade} term is negative since the micro-trip is for a downhill driving condition.

The probable issue for the downhill micro-trips is that, for some micro-trips the modification ratio may need to be very low, leading to very short micro-trips. Obviously, the problem for such conditions is not having a short micro-trip but it is having a micro-trip with a very high, unrealistic acceleration. Especially for low speed driving conditions; where W_{roll} and W_{aero} are relatively low and for very steep downhill conditions; where the W_{grade} is relatively high, it may be needed to choose a very low modification ratio in order to compensate the negative grade work. For such conditions, modification ratio is limited to a pre-determined value such that the acceleration of the modified micro-trip does not surpass a specific limit. Obviously, when the modification ratio is limited according to acceleration, the grade work for this specific micro-trip is not fully compensated.

4.3 Case Study: Historical Peninsula (Haliç)

In this chapter, a case study for embedding road grade effect into a driving cycle is demonstrated for Historical Peninsula route, based on the methodology presented in this chapter. Please note that all the figures and values in this chapter are given to set an example for embedding road grade effect. These values strongly depend on the topography of the selected route, therefore may change for different trajectories.

A typical trip in the Historical Peninsula is assumed as a real world driving cycle. The speed profile of the trip is given in Figure 4.3.

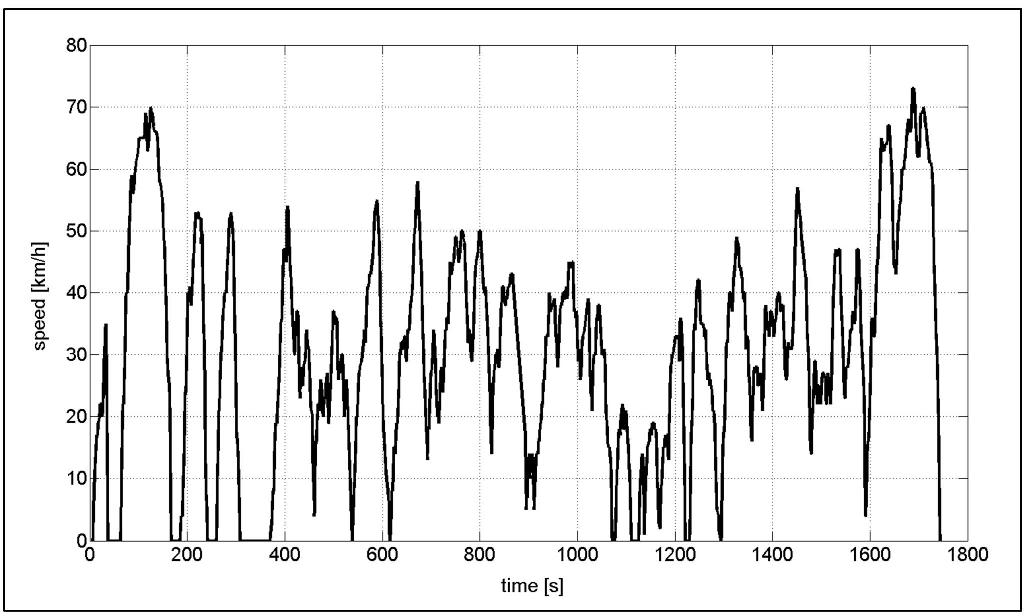

Figure 4.3 : Speed profile of Historical Peninsula trip.

The height profile of the route is given in Figure 4.4. As mentioned before, spline-fitting approach is applied in order to smooth the height data obtained from the GPS sensor.

The grade profile of the route is derived from the height data by differentiating it with respect to distance. The resulting grade profile of the route is given in Figure 4.5.

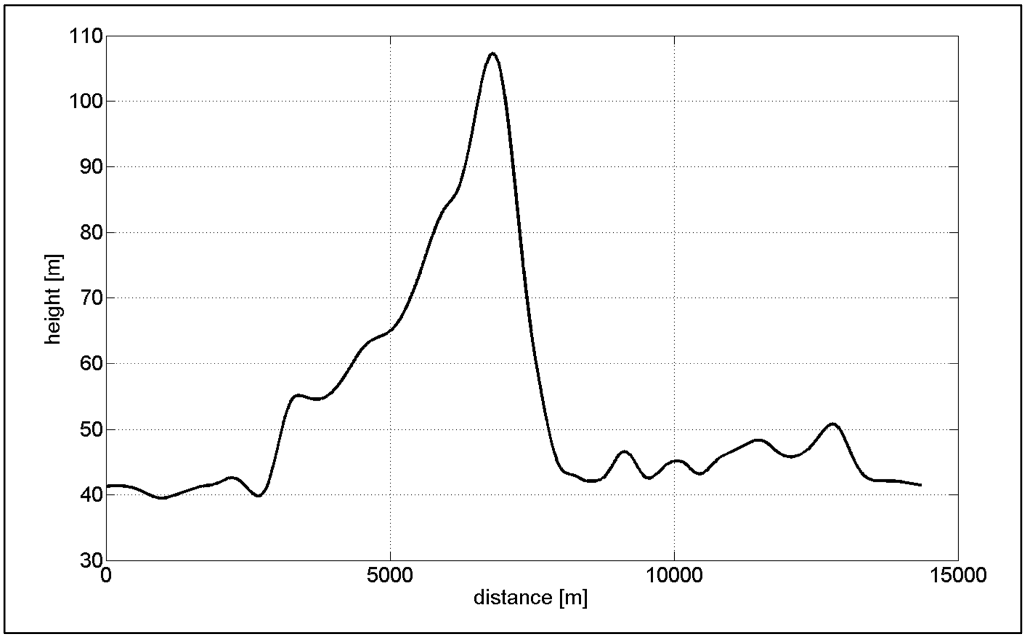

Figure 4.4 : Height profile of Historical Peninsula route.

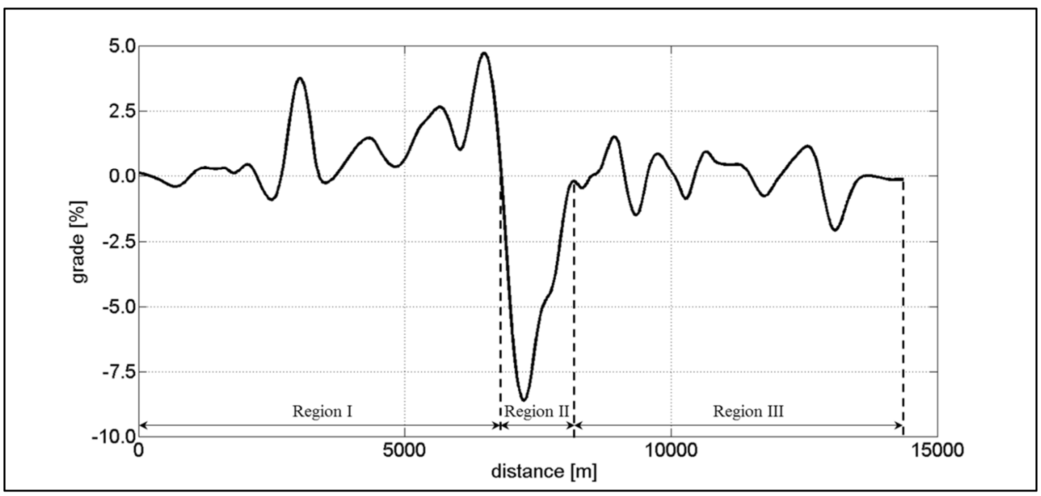

Figure 4.5 : Grade profile of Historical Peninsula route.

The route is divided into three regions according to the grade characteristics. The main motivation to divide the route into different parts is to highlight the relationship between road grade and the compensating capacity of the presented algorithm. The first region contains mostly uphill paths. For this region, micro-trip durations are mostly increased to represent the additional grade work. The second region contains downhill paths with very high grades. For this region, micro-trip durations are decreased significantly to compensate for the very high negative grade work. The third region contains both uphill and downhill paths with relatively low grades. The highest uphill grade is observed in the first region, which is 4.7%. The highest downhill grade is observed in the second region, which is 8.6%.

The results of the modifications to embed road grade effect are given region by region in Table 4.1.

Table 4.1 : Analysis of results for Historical Peninsula route.

Parameter	Uphill	Downhill
Region I		
Total grade work	1041 kJ	-77 kJ
Grade work represented	1041 kJ	-77 kJ
Grade work represented as %	100 %	100 %
Total Grade work represented as %	100 %	
Distance of original trip	6.73 km	
Distance of modified trip	10.32 km	
Region II		
Total grade work	0 kJ	-891 kJ
Grade work represented	0 kJ	-249 kJ
Grade work represented as %	-	28 %
Total Grade work represented as %	28 %	
Distance of original trip	1.41 km	
Distance of modified trip	0.50 km	
Region III		
Total grade work	253 kJ	-276 kJ
Grade work represented	253 kJ	-272 kJ
Grade work represented as %	100 %	99 %
Total Grade work represented as %	99 %	
Distance of original trip	6.07 km	
Distance of modified trip	6.02 km	
Total Trip		
Total grade work	1294 kJ	-1244 kJ
Grade work represented	1294 kJ	-598 kJ
Grade work represented as %	100 %	48 %
Total Grade work represented as %	75 %	
Distance of original trip	14.21 km	
Distance of modified trip	16.84 km	

As seen in Table 4.1, for the first region uphill grade work is more dominant than downhill. That is due to the topography of the first region, which contains mostly uphill paths with maximum grade of 4.7%. In order to represent this positive grade work the durations of the micro-trips are increased and therefore, the trip distance increases from 6.73 km to 10.32 km. The percentage of grade work representation is

100% for this region. In other words, all of the grade work is embedded into the modified trip.

The second region consists of all downhill micro-trips, with maximum grade of 8.6%. In order to represent this negative grade work the durations of the micro-trips are decreased and therefore, the trip distance decreases from 1.41 km to 0.50 km. The percentage of grade work representation is only 28% for this region. In other words, 28% of the grade work is embedded into the modified trip. This is due to the fact that this region contains micro-trips having downhill paths with very high grades. Modification ratios need to be very low values in order to compensate this high negative grade work. However, they cannot be lower than a pre-determined value because the acceleration of the modified micro-trip should not surpass a specific limit. Due to this limit, the grade work for these micro-trips cannot be fully compensated.

The third region consists of both uphill and downhill grades with relatively low grades. As seen in the table, uphill and downhill grade works are very close to each other. As a result of this, the trip distance does not change significantly. It decreases from 6.07 km to 6.02 km. The percentage of grade work representation is 99% for this region. In other words, almost all of the grade work is embedded into the modified trip. The 1% of the total grade work that cannot be represented for this region belongs to the downhill section. The unrepresented downhill grade work is very small compared to the second region due to the fact that the maximum downhill grade does not surpass 2.0% for this region.

Considering the total trip, the percentage of grade work representation is 100% for uphill paths and 48% for downhill paths. Please note that, even though the distance of the second region is very low compared to the total trip, the unrepresented downhill grade work makes a significant contribution to the final representation percentage. This is due to the fact that the representation percentages are computed with respect to the magnitude of work and the magnitude of the downhill grade work is very high in the second region. The total grade work representation for the overall trip is 75%. The speed profiles of the original Historical Peninsula route and the modified trip are given in Figure 4.6.

Please note that all the figures and values presented in this chapter are given to set an example for embedding road grade effect. Total and represented grade work values strongly depend on the topography of the selected route, therefore may change for different trajectories. Please also note that the final modified trip given in Figure 4.6 is not a driving cycle for Historical Peninsula. This is just a case study demonstrating the application of the presented methodology for embedding road grade effect.

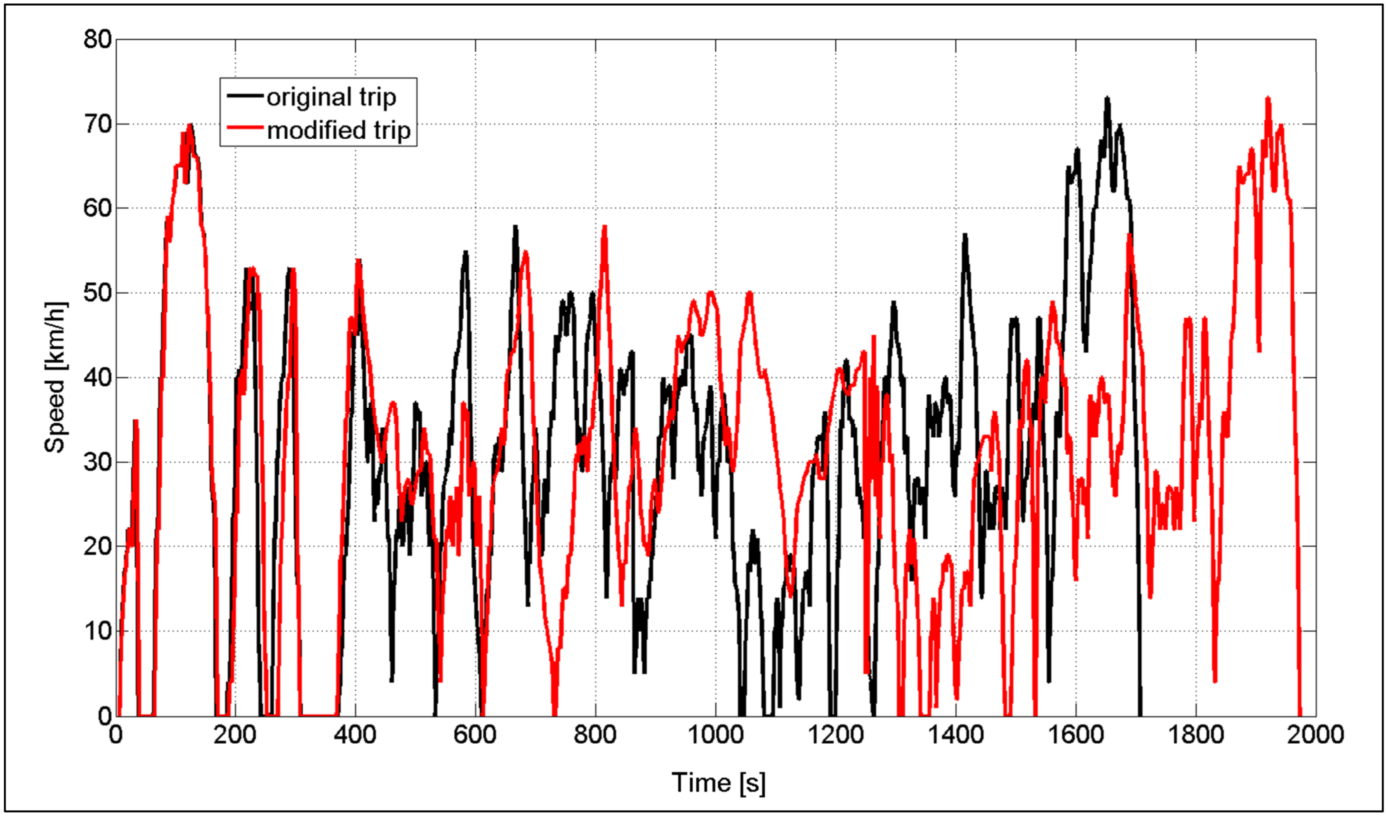

Figure 4.6 : Comparison of original and modified trips.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Discussion of Results

Vehicle exhaust emissions and emission factors are strongly affected by driving conditions; therefore identifying the driving patterns in a specific region plays a crucial role for the accurate estimation of vehicle emissions. The driving pattern in a specific region can be represented as a driving cycle, which is a vehicle speed-time profile. Driving conditions can then be simulated on a laboratory chassis dynamometer with the aid of this speed-time profile in order to evaluate fuel consumption, exhaust emissions and vehicle emission factors.

In this thesis, a methodology is proposed to develop a real-world driving cycle for the estimation of exhaust gas emissions of road vehicles. Then, a practical application of this methodology is put into practice for the city of İstanbul and İstanbul Driving Cycle (IDC) is generated. When the characteristics of the generated driving cycle are compared with the regional characteristics, it is seen that less than 5% error is obtained for the comparison criteria of idling percentage, average speed, average acceleration, average deceleration, average positive specific power and average negative specific power. Therefore, it can be concluded that the generated driving cycle represents the driving characteristics of İstanbul accurately.

Meanwhile, with a concurrent study, the İstanbul Driving Cycle (IDC) generated in this thesis is compared with the legislative cycles of USA (FTP75: Federal Test Procedure) and Europe (NEDC: New European Driving Cycle). All three cycles are compared in terms of fuel economy and exhaust emissions with dynamometer tests, which are carried out with thirty passenger cars with spark ignition engine of different model year and emission control technology. The model years and emission control technologies of the test vehicles are selected to reflect the passenger car fleet with spark ignition in Turkey. According to the results, the fuel consumption and exhaust emissions values obtained with IDC are quite different from the values obtained with FTP75 and NEDC. These results show that, the regional driving characteristics of İstanbul; hence, the exhaust emissions cannot be represented accurately with legislative cycles of FTP75 and NEDC. More generally speaking, for the accurate estimation of vehicle emissions in a specific region, the unique driving patterns of this region need to be identified in the form of a real world driving cycle, which is constituted of real world driving data collected in this specific region.

5.2 Recommendations and Next Steps

Driving characteristics in a specific region can change due to various factors. Changes in the population of the region or car fleet, implementation of new public transportation facilities are just a few examples. In such cases, real world data acquisition and analysis operations need to be updated to reflect the most recent driving characteristics. A more robust way is to repeat real world data acquisition at regular intervals and update the driving cycle accordingly. By doing so, the effect of the factors mentioned above on driving characteristics, hence the exhaust emissions and emission factors, can be studied.

The case study of İstanbul Driving Cycle represents the average traffic flow and is valid only for passenger cars and light duty vehicles. Heavy duty vehicles and special vehicle operations cannot be represented with İstanbul Driving Cycle because they have completely different vehicle characteristics; such as vehicle mass and acceleration ability. However, the driving cycle construction methodology presented in this thesis can be implemented for any type of road vehicle; such as a public bus driving cycle.

The driving cycle construction methodology presented in this thesis can also be utilized for different cities, regions. Hence, specific regional driving cycles can be generated. Furthermore, special driving cycles to be utilized in vehicle design development and durability studies can be generated with the aid of the developed methodology.

Real world driving data is collected in actual traffic conditions, where there is altering road grade. A driving cycle is generated from this real world driving data and it is simulated on a flat chassis dynamometer. In this situation, the effect of road grade is not included. The contribution of this grade work depends on topography and driving conditions. In the last chapter of the thesis, a methodology is presented to embed the road grade effect into a driving cycle. The main motivation is to find a universal solution such that the grade effect can be represented on a conventional dynamometer without any need for a hardware or software update. The presented methodology proposes to modify micro-trips with respect to time such that the grade work experienced in the real world conditions is embedded in the driving cycle.

The concept of embedding road grade effect into a driving cycle may be more comprehensively studied. The presented methodology modifies only the time durations of the micro-trips to embed the grade effect. The most significant advantage of this method is that micro-trip velocities are not altered; therefore, the deterioration of the original driving data is relatively low. Modifications of the micro-trips can be carried out also with respect to velocity. However, for this case the deterioration of the real world driving data is higher than the proposed method in this thesis. In other words, there is a trade-off between the grade work representativeness and the deterioration of the real world driving conditions. In future work, with a dynamometer setup that can represent the instantaneous grade force; the driving cycle developed with different methodologies can be compared with each other in terms of exhaust emission rates.

5.3 Conclusions

In this thesis, a methodology is developed to construct a real-world driving cycle for the estimation of exhaust gas emissions of road vehicles. This methodology is applicable to any road vehicle. For instance, a driving cycle specific for a bus route can be generated with this methodology. Real world statistical data is collected on pre-defined routes and this data is sequenced into micro-trips. Series of micro-trips are selected with a quasi-random approach until the traveled distance of the driving cycle reaches a predefined limit. Each developed driving cycle is evaluated with respect to the real world test data by using specific comparison criteria and the driving cycle that best represents the driving characteristics of the specific region is chosen as the final driving cycle.

Apart from methodology development, a practical application of this methodology is applied for the city of İstanbul. Real world driving data is collected in pre-determined routes in İstanbul with a passenger car. Real world traffic data is collected in morning and evening peak traffic conditions as well as off-peak conditions; both in weekdays and weekends and a driving cycle is generated for the city of İstanbul. When the characteristics of the generated driving cycle are compared with the regional characteristics, it is seen that less than 5% error is obtained for the comparison criteria of idling percentage, average speed, average acceleration, average deceleration, average positive specific power and average negative specific power every comparison criteria. Therefore, it can be concluded that the regional driving characteristics of İstanbul are represented very accurately with the generated driving cycle. Moreover, according to the results of the dynamometer tests conducted with IDC, NEDC and FTP75, the regional driving characteristics of İstanbul; hence the exhaust emissions cannot be represented accurately with legislative cycles of FTP75 and NEDC. For the accurate estimation of vehicle emissions in a specific region, the unique driving patterns of this region need to be identified in the form of a real world driving cycle.

REFERENCES

Andre, M. (2004). The ARTEMIS European driving cycles for measuring car pollutant emissions. *Science of the Total Environment, 334-335,* 73-84.

Booth, A., Muneer, T., Kirby, H., Kubie, J., Hunter, J. (2001). The measurement of vehicular driving cycle within the city of Edinburgh. *Transportation Research Part D, 6,* 209-220.

Cayot, J. F., (1995). The fight against automotive pollution. An opportunity or a threat for diesel engines? *Istanbul 1st International Automotive Industy and Environment Conference and Exhibition*, May 1995, 113-122.

Charbonnier, M. A., Andres, M. (1993). A comparative study of gasoline and diesel passenger car emissions under similar conditions of use. *SAE Technical Paper Series,* 930779.

Dinc, C., Sorusbay, C., Ergeneman, M., Goktan, A. G. (2012). Development of a driving cycle for the estimation of vehicle emissions. *OTEKON 2012, 6. Otomotiv Teknolojileri Kongresi*, Bursa, Turkey, June 5.

Ergeneman, M., Soruşbay, C., Göktan, A. (1997). Development of a driving cycle from road traffic measurements for the prediction of pollutant emissions and fuel consumption. *International Journal of Vehicle Design*, *18*, No. 3/4.

Ergeneman, M., Soruşbay, C., Göktan, A. (2010). Estimation of greenhouse gas emissions related to urban driving patterns**,** *ICAT 2010*, İstanbul.

Gerçek, H., Çelikoğlu, H. B. (2011). *Ulaştırma sektöründe sera gazı azaltımı: TÜBİTAK Project 105G039 Report,* İTÜ, İstanbul.

Gillespie T. D. (1992). *Fundamentals of vehicle dynamics*. Society of automotive engineers (SAE), Warrendale, PA, USA.

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., Linden, P. J., Dai, X., Maskell, K., Johnson, C.A. (2001). *IPCC, 2001: Climate change 2001: The scientific basis. Contribution of working group I to the third assessment report of the intergovernmental panel on climate change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Hung, W. T., Tong, H. Y., Lee, C. P., Ha, K., Pao, L.Y. (2007). Development of a practical driving cycle construction methodology: a case study in Hong Kong. *Transportation Research Part D, 12,* 115-128.

Kamble, S. H., Mathew, T. V., Sharma, G. K. (2009). Development of a real-world driving cycle: case study of Pune, India. *Transportation Research Part D, 12,* 132-140.

Kojima, K., Ryan, L. (2010). *IEA: Transport Energy Efficiency. Implementation of IEA recommendations since 2009 and next steps*, IEA: International Energy Agency, Paris, France.

Le Treut, H. R., Somerville, U., Cubasch, Y., Ding, C., Mauritzen, A., Mokssit, T., Peterson, T., Prather, M. (2007). *Historical overview of climate change. in: Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Lin, J., Niemeier, D. A. (2002). An exploratory analysis comparing a stochastic driving cycle to California's regulatory cycle. *Atmospheric Environment, 36,* 5759-5770.

Özturk, T.A. (2010). *İstanbul şehir çevriminin ABD ve Avrupa test çevrimleri ile emisyon faktörleri ve yakıt tüketimi açısından deneysel olarak karşılaştırılması*, (Yüksek lisans tezi), İTÜ, İstanbul.

Pelkmans, L., Debal, P. (2006). Comparison of on-road emissions with emissions measured on chassis dynamometer test cycles. *Transportation Research Part D, 11,* 233-241.

Soruşbay, C., Ergeneman, M., Öztürk, T.A.H., Sel, E. (2010). Binek araçlarında sürüş koşullarının kirletici egzoz emisyonlarına etkisi. *HKK2010, IV. Ulusal Hava Kirliliği ve Kontrolü Sempozyumu,* ODTÜ Kültür ve Kongre Merkezi, Ankara, Turkey, 25-27 October.

Tong, H. Y., Hung, W. T., Cheung, C. S. (1999). Development of a driving cycle for Hong Kong. *Atmosperic Environment, 33,* 2323-2335.

Tzirakis, E., Pitsas, K., Zannikos, F., Stournas, S. (2006). Vehicle emissions and driving cycles: comparison of the Athens driving cycle (ADC) with ECE-15 and European driving cycle (EDC), *Global NEST Journal, 8* (3), 282-290.

Watson, C. H. (1995). Effects of a wide range of drive cycles on the emissions from vehicles of three levels of technologies, *SAE Technical Paper Series,* 950221.

Yu, L., Wang, Z., Qiao, F., Qi, Y. (2008). Approach to development and evaluation of driving cycles for classified roads based on vehicle emission characteristics. *Transportation Research Record: Journal of Transportation Research Board, 2058*, 58-67.

CURRICULUM VITAE

Name Surname: Cenk Dinç

Place and Date of Birth: İstanbul, 15.07.1981

E-Mail: dinccenk@gmail.com

B.Sc.: İTÜ - Mechanical Engineering, (2004) (**high honor's degree**).

1st Place in Automotive Department, GPA:3.67/4.00.

M.Sc.: Koç University - Mechanical Engineering, (2006) (**with full scholarship**).

GPA: 3.96 / 4.00.

Ph.D.: İTÜ - Mechanical Engineering, (2013) GPA: 4.00 / 4.00

Professional Experience

2012-…. Ford Otosan *Project Engineer* / PD

2010-2012 Ford Otosan *Team Leader* / PD

2008-2010 Ford Otosan *Lead Engineer* / PD

2006-2009 İTÜ *Research Scholar*

2004-2006 Koç University *Research and Teaching Assistant*

Rewards:

1st Place in Turkey, in ranking of PhD Scholars in Mechanical Engineering (2009)

TÜBİTAK Doctorate Scholarship (2009)

International Scientific Publications Promotion, Turkish Academic Network (2009)

TÜBİTAK Research Fellowship (2007)

Top 100 in Turkey in the Entrance Examination for Graduate Studies, LES (2005)

TÜBİTAK Post-Graduate Scholarship (2005)

Vehbi Koç Scholarship (2004)

High Honors' List of ITU 2004 Graduates (2004)

1st Place in ITU Mechanical Engineering - Automotive Department (2004)

List of Publications and Patents:

▪ **Dinc C.**, Arslan O., Akgun T., Almenar R., 2010: Improvement of Engine Cooling Performance for a Construction Truck using Numerical and Experimental Methods. *SAE*, 2010-01-2054.

▪ **Dinc C.**, Arslan H., Mehdiyev R., 2009: CO_2 Emission Reduction Using Stratified Charge in Spark Ignition Engines. *Energy&Fuels*, Volume 23, Issue 4, 1781-2318.

▪ Ulutan D., Lazoglu I., **Dinc C.**, 2009: Three-Dimensional Temperature Prediction in Machining Processes Using Finite Difference Method. *Journal of Materials Processing Technology*, Elsevier Science Ltd., Volume 209, 1111-1121.

▪ **Dinc C.**, Lazoglu I., Serpenguzel A., 2008: Analysis of Thermal Fields in Orthogonal Machining with Infrared Imaging. *Journal of Materials Processing Technology*, Elsevier ScienceLtd, Volume 198, 147-154.

▪ Lazoglu I., Ulutan D., **Dinc C.**, 2008: 3D Temperature Fields in Machining. *3rd CIRP International HPC Conference*, Dublin, Ireland, June 2008.

▪ **Dinc C.**, Lazoglu I., Serpenguzel A., 2007: High Precision Infrared Thermal Measurements in Orthogonal Machining. *Proceedings of 4th International Conference and Exhibition on Design and Production of Machines and Dies/Molds*, İzmir, Turkey, June 2007.

PUBLICATIONS/PRESENTATIONS ON THE THESIS

▪ **Dinc C.**, Sorusbay C., Ergeneman M., Göktan A. G., 2012: Development of a Driving Cycle for the Estimation of Vehicle Emissions. *OTEKON 2012, 6. Otomotiv Teknolojileri Kongresi*, Bursa, Turkey, June 5.