1. Report No. SWUTC/10/169300-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle PEMS-BASED APPROACH TO DEVELOPING AND EVALUATING DRIVING CYCLES FOR AIR QUALITY ASSESSMENT		5. Report Date April 2010 6. Performing Organization Code
7. Author(s) Lei Yu, Ziqianli Wang, and Qinyi Shi		8. Performing Organization Report No. Report 169300-1
9. Performing Organization Name and Address Texas Southern University 3100 Cleburne Avenue Houston, TX 77004		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 10727
12. Sponsoring Agency Name and Address Southwest Region University Transportation Center Texas Transportation Institute Texas A&M University System College Station, Texas 77843-3135		13. Type of Report and Period Covered Research Report September 2008 – August 2009 14. Sponsoring Agency Code
15. Supplementary Notes Supported by general revenues from the State of Texas.		

16. Abstract

A driving cycle is the fundamental concept in conducting emission testing and modeling. The quality of a driving cycle is directly associated with the accuracy of any air quality analysis, and therefore whether the emission reductions can be achieved. However, the widely used driving cycles bring considerable uncertainties when the emission estimation is carried out for a specific city or region. Further, the existing driving cycles have been developed based only on the driving activities, without capturing the characteristics of emission profiles. In this context, this research is intended to achieve two primary objectives. The first objective is to develop driving cycles for classified roads incorporating both a vehicle's driving activities and its emission characteristics, using the data collected by Portable Emission Measurement System (PEMS), which was neither available nor has ever been used in developing driving cycles. A comprehensive database is established for the collected data and a sophisticated computer program is developed to generate the specific driving cycles. The second objective is to develop an evaluation approach of driving cycles in which Vehicle Specific Power (VSP), a parameter that can readily connect the driving modes with emissions, is used to evaluate how well the driving cycles can represent the driving and emission characteristics on real roads. The proposed methodology for generating driving cycles is then evaluated for its effectiveness on the emission estimation based on a comparative analysis with the current emission inventory and traditional methodologies.

17. Key Words Portable Emissions Measurement Systems (PEMS), Driving Cycles, Driving Activities, Emission Characteristics, Emission Model, Emission Inventory, Vehicle Specific Power (VSP), Evaluation Method		18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161	
19. Security Classify (of this report) Unclassified	20. Security Classify (of this page) Unclassified	21. No. of Pages 94	22. Price

PEMS-based Approach to Developing and Evaluating Driving Cycles for Air Quality Assessment

by

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Report SWUTC/10/169300-1

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April 2010

ABSTRACT

A driving cycle is the fundamental concept in conducting emission testing and modeling. The quality of a driving cycle is directly associated with the accuracy of any air quality analysis and, therefore, whether the emission reductions can be achieved. However, the widely used driving cycles bring considerable uncertainties when the emission estimation is carried out for a specific city or region. Further, the existing driving cycles have been developed based only on the driving activities, without capturing the characteristics of emission profiles. In this context, this research is intended to achieve two primary objectives. The first objective is to develop driving cycles for classified roads incorporating both a vehicle's driving activities and its emission characteristics, using the data collected by Portable Emission Measurement System (PEMS), which was neither available nor has ever been used in developing driving cycles. A comprehensive database is established for the collected data and a sophisticated computer program is developed to generate the specific driving cycles. The second objective is to develop an evaluation approach of driving cycles in which Vehicle Specific Power (VSP), a parameter that can readily connect the driving modes with emissions, is used to evaluate how well the driving cycles can represent the driving and emission characteristics on real roads. The proposed methodology for generating driving cycles is then evaluated for its effectiveness on the emission estimation based on a comparative analysis with the current emission inventory and traditional methodologies. Results show that driving cycles developed by the proposed method can better represent the emission characteristics of on-road vehicles.

EXECUTIVE SUMMARY

Transportation-related emissions are becoming one of the principal contributors to air pollution and Greenhouse Gas (GHG) emissions. In order to develop air quality inventories and implement emission control strategies, the driving cycle is an important concept that has been applied for many years for the purpose of emission testing and estimation. The quality of a driving cycle is directly associated with the accuracy of any air quality analysis and, therefore, whether the emission reductions can be achieved. However, due to the limitation of real-world source data, a lack of comprehensive driving cycle classification, and the sort of effective driving cycle evaluation method, the widely used driving cycles bring considerable uncertainties when the emission estimation is carried out for a specific city or region. Further, the existing driving cycles have been developed based only on the driving activities, without capturing the characteristics of emission profiles. In this context, the primary objectives of this research are to: (1) develop driving cycles for classified roads incorporating both a vehicle's driving activities and its emission characteristics; and (2) develop an evaluation approach of driving cycles in which Vehicle Specific Power (VSP) is adopted to evaluate how well the driving cycles can represent the driving and emission characteristics on real roads.

The data collection is the first step for the development of driving cycles. This research used Portable Emission Measurement System (PEMS) and Global Positioning System (GPS) to collect the instantaneous vehicle activity data. After the data collection, the data preprocessing was conducted and a specific database was built in which each record includes the activity and emission information at every second. The methodology for developing driving cycles is composed of six steps: (1) Classify the data source into four groups according to facility types; (2) Split data in each group into microtrips in terms of speed; (3) Calculate activity and emission measures for each microtrip and the whole group data; (4) Develop the microtrip's pool; (5) Develop candidate driving cycles' pool; and (6) Pre-select the best representative driving cycles. Finally, an evaluation method of driving cycles based on the concept of VSP, a parameter that can readily connect the driving modes with emissions, is used to present how much each driving cycle can represent real world driving conditions and relevant emission characteristics.

The following conclusions are provided based on this research:

First, PEMS is a useful technology for emission measurement. It provides a unique approach for collecting real-time emissions as well as driving activity data—both of which are essential for the development of new generation driving cycles.

Second, the proposed methodology for developing driving cycles is practical. It not only takes driving activity measures into consideration, but also considers emission characteristics as additional measures to develop driving cycles. Such driving cycles are able to better represent driving conditions as well as emission characteristics in a real world condition.

Third, VSP is promising in the field of on-road emission research. It can be easily obtained and includes information on driving conditions such as idling and cruising. Furthermore, the sensitivity analysis indicates that VSP has more comprehensive correlations with different emissions in both the low and high speed ranges.

Fourth, the VSP-based evaluation method for driving cycles is effective. In this research, VSP was utilized to assess driving cycles in terms of emission characteristics. Besides the similarity of the emission condition, the final driving cycles determined by the VSP-based evaluation method also record a vehicle's driving activity.

Finally, the new driving cycles developed by the proposed methodology are able to properly reflect the different driving conditions in various types of facilities. In the case study, there was a relatively high proportion of idling on minor arterials because there were significant conflicts between vehicles, cyclists, and pedestrians which delayed driving. Furthermore, most emissions were generated on minor arterials.

Considering the findings and conclusions, this report provides six recommendations for future studies to further improve the research in this report.

1. It is recommended that driving cycles be developed using VSP as the key criteria instead of activity and emission measures.

2. It is recommended that driving cycles for heavy duty vehicles and for vehicles using other types of fuels be developed.

3. It is recommended that the factor of fuel consumption be consisted as another key control measure in the development of driving cycles.

4. It is recommended that more real-world vehicle activity and emission data be collected to further expand the available database. It is also recommended that the testing areas be expanded, so that the comparison of driving cycles between various study areas can be conducted.

5. It is recommended that urban driving patterns and fuel consumption patterns be systematically linked with driving cycles, which can then be used to estimate spatial differences in transport energy use per capita.

6. It is recommended that a VSP-based emission model be developed based on the existing emission database.

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DISCLAIMER

ACKNOWLEDGMENT

The authors recognize that support for this research was provided by a grant from the U.S. Department of Transportation, University Transportation Centers Program to the Southwest Region University Transportation Center which is funded, in part, with general revenue funds from the State of Texas.

CHAPTER 1: INTRODUCTION

1.1 Background of Research

At the present time, environmental problems have become a critical threat to the healthy and rapid development of modern society. Among the environmental problems, transportation-related emissions are one of the principal contributors to air pollution and Greenhouse Gas (GHG). We, here, undertake a comprehensive study in response to this challenge and the corresponding research aims to make a significant contribution to solving the problem. Corresponding emission control strategies are planned in order to control and reduce transportation related emissions. The effectiveness of these strategies, however, is completely dependent on accurate emission estimations. In light of the emission estimations, the driving cycle is an important concept that has been applied for many years in the emission estimation for the purpose of emission control and regulation. However, the accuracy of the emission estimation based on the concept of driving cycles still needs further improvement, and an efficient evaluation method of driving cycles should be explored. The present study proposes a new approach to developing driving cycles that is based upon not only vehicle activity characteristics, but also vehicle emission characteristics. This new approach is different from existing methods, and it will better represent real world driving conditions and provide more accurate emission estimations. Furthermore, an evaluation method based on Vehicle Special Power (VSP) as well as the application of driving cycles are also presented in this report.

1.1.1 On-Road Transportation Related Emissions

Air pollution is a primary environmental problem for major metropolitan areas. Among the many types of pollutant sources, transportation-related emissions are a major source of the criteria pollutants and hazardous air pollutants that are ubiquitous in urban areas in the United States and worldwide (Marshall, et al., 2005). Transportation related emissions can be categorized as either “on-road” or “off-road” based on their sources. The "on-road" sources include vehicles used on roads for transportation of passengers or freight, and the “off-road" sources include vehicles, engines, and equipments that are used for transportation purposes other than “on-road”. Specifically, the off-road categories include aircraft, vessels, construction vehicles, and small engines such as airport support vehicles, crawler tractors (for agricultural logging). In the two broad categories, on-road sources contribute a larger part of the total emissions from the transportation sources. In 2000, on-road transportation sources accounted for 44 perecent of carbon monoxide (CO) emissions, 33percent of nitrogen oxide (NOx) emissions, and one percent of particulate matter (PM) emissions (CCCEF, 2007). Additionally, as on-road emissions usually occur in population dense areas where a lot of residents live, they therefore have a greater impact on air quality and consequently have received more attention in research. Furthermore, the continually increased on-road vehicle population has resulted in complex traffic problems with serious knock-on consequences on emissions and fuel consumption. Therefore, it is vital for researchers to estimate vehicle exhaust emissions and fuel consumption accurately in order to develop effective control strategies. In this study, the driving cycle is to represent and characterize the driving conditions of the real world in order to estimate emissions from on-road sources.

1.1.2 Emission Control Strategies

In facing the severe air pollution problems, positive and efficient emission control strategies have been applied to reduce vehicle emissions for decades. In general, emission control strategies implemented in different countries may be grouped into two categories, which could be defined here as: static control strategies and dynamic control strategies (Wiersma, 2004).

The so-called static emission control strategies include those that are associated with the improvement of vehicles and fuels, including: (1) engine control technique, such as the improvement of fuel injection, ignition, waste gas recycling, etc.; (2) catalyst conversion technique, such as oxidation catalysis, reduction catalysis, etc.; and (3) fuel amelioration or replacement, such as unleaded gasoline, ethanol, etc. With applications of these static control techniques, there has been a significant reduction of emissions by individual vehicles. For example, individual automobile exhausts of CO, Hydrocarbon (HC) and NOx have been reduced by 95percent, 96percent and 92percent (Ryan & Throgmorton, 2003) respectively with applications of static control strategies. However, as the number of vehicles and vehicle miles traveled (VMT) or vehicle kilometers traveled (KMT) increase continuously, the urban air quality problem still exists and is even deteriorating—especially in developing countries—and hence the traditional static control strategies have become less effective.

Dynamic emission control strategies have been developed, which primarily include those that are related to the enhancement of transportation and management strategies, such as: (1) urban planning and transportation planning that intend to reduce trips by efficient land use and to reduce emissions by specific road planning; (2) traffic control and deployment of Intelligent Transportation Systems (ITS) technologies including transit priority and integrated optimization of traffic quality that intends to smooth traffic flow; and (3) management policies such as the limitation of maximum weight of vehicle load, etc. Compared with static control strategies, dynamic control strategies emphasize trip generation, distribution and assignment with an intention to effectively control emissions by changing driving behaviors.

In order to implement any of the above emission control strategies and/or technologies, accurate estimation of emissions in various traffic networks is critically important. In other words, if the accurate estimation of emissions is not achieved, the feasibility and effectiveness of any strategies cannot be decided.

1.1.3 Emission Estimation Methodologies

As discussed earlier, an accurate estimation of emissions is critical for implementing any emission control strategy. Studies on the estimation of vehicle emissions have focused on the development of various emission estimation models, such as the MOBILE emission factor model developed by the United States Environmental Protection Agency (EPA) (EPA, 2003), the Motor Vehicle Emission Simulator (MOVES) developed by the EPA (Glover, 2004), the EMFAC model developed by the California Air Resource Board (CARB) (CARB, 2007), International Vehicle Emission (IVE) model developed by Environmental Research and Technology (CE-CERT) (GSSR, 2004b), and the COPERT model developed by the European Commission Environmental Protection Agency (Ntziachristos & Samaras, 2000), as well as quantification relationships between transportation planning, land use, traffic control, ITS and vehicle emissions. MOBILE has been designated by the EPA as the emission factor model for all states in United States (with the exception of California). It is built upon basic driving cycles, which will be introduced in the next chapter; they are derived from the Federal Test Procedure (FTP). MOBILE, EMFAC, and COPERT are classified as macroscopic emission models, which use driving cycles as the point of departure to calculate basic emission factors, which are then adjusted according to speed, temperature, fuel and other relevant elements. The above three macroscopic models have used similar basic concepts regarding driving cycles.

However, the macroscopic emission model cannot accurately estimate real time emissions when vehicles are running on the roads, because driving patterns in different cities result in big differences in terms of basic driving cycles. For instance, when considering two cars with the same average speed, this may result from completely different driving patterns on different roads because of unique traffic and geographic conditions that would cause a significant difference in emissions. This difference is not measurable at the macroscopic level.

To address the above deficiency of macroscopic emission models, two approaches can be adopted.

One is to develop microscopic emission models based on real time driving modes. For examples, the Mobile Emission Assessment System for Urban and Regional Evaluation (MEASURE) is a GIS-based microscopic emission model developed by the Georgia Institute of Technology (Bachman, 2000). The University of California, Riverside developed the Comprehensive Modal Emissions Model (CMEM) (Barth, 2000) and Texas Southern University developed the microscale emission model by using infrared remote sensing technology (Yu, 1998). A microscopic model is able to trace instantaneous variations in emissions from each vehicle. This sort of model achieves accurate estimations but requires traffic data at a high level of accuracy. Besides, many traffic simulation models such as INTEGRATION, CORSIM, and TRANSIMS, have embedded their own microscopic emission evaluation models, which can estimate the mass of emissions under various traffic situations. However, the validity and accuracy of these models have not been well established by existing research.

Another way to address the deficiency of the macroscopic emission model is to construct specific driving cycles for different road types and traffic conditions. For example, EPA provides the Supplement Federal Test Procedure (SFTP) which is effective after the model year 2000 engine to address the shortcomings with the FTP-75 test cycle, which is a driving cycle that has been used for emission certification of light duty vehicles in the United States. SFTP provides a more accurate representation of aggressive (high speed and/or high acceleration) driving behavior, rapid speed fluctuation, and the driving behavior following startup. Moreover, there have been many other driving cycles developed for other cities, such as the Athens Driving Cycle (ADC) (Tzirakis, et al., 2006) and "TEH_CAR" cycle for Iran (Montazeri-Gh & Naghizadeh, 2003).

1.2 Concept of Driving Cycle

A driving cycle is an important concept in quantifying vehicle emissions for the purpose of emission controls and is depicted by a series of data points representing the speed of a vehicle versus time. It represents the typical and average driving conditions of a trip or portions of a trip in a study area and simulates the vehicle's driving conditions from start to finish. Figure 1 shows the new California Urban driving cycle (called Cal-Urban) as a sample driving cycle. The Cal-Urban driving cycle has top speeds in excess of 70 miles per hour (mph) and includes several acceleration-deceleration "hills" with a top speed in excess of 40 mph.

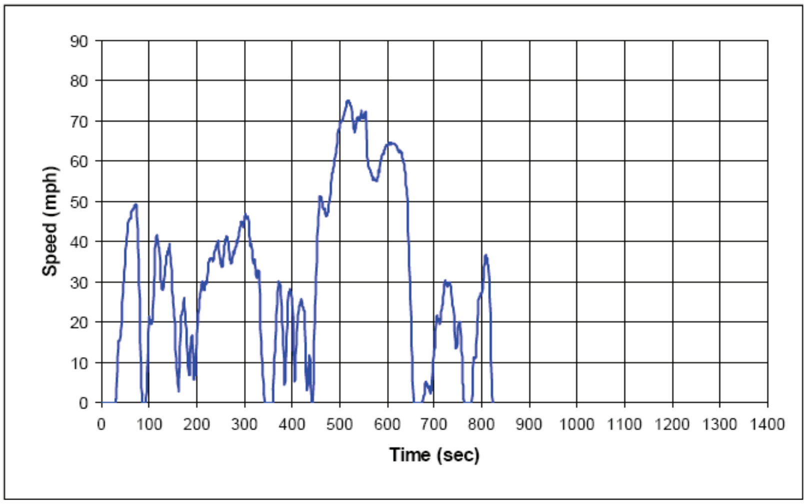


Figure 1 Cal-Urban Driving Cycle Speed-Time Trace

Source: Sierra Research, Inc. (Austin, et al., 2008)

Driving cycles are used to assess the performance of vehicles in various ways and, as the most common example, to assess polluting emissions and fuel consumption in vehicle certification programs. Emission and fuel consumption tests are performed on the chassis dynamometer which is designed for determining the power of an electric motor or engine of a car, truck, or other vehicle. Tailpipe emissions are collected and measured to indicate the performance of the vehicle. With driving cycles, vehicle emission rates can be calculated for the purpose of air quality inventories and emission controls. Most of the macroscopic emission factors modeling systems have used the concept of driving cycles for the collection of their essential data. On the other hand, the microscopic emission models use driving cycles to transform instantaneous emissions into average emission factors.

Consequently, the development of driving cycles does not only affect the accuracy of vehicle emission estimations, but also provide a method to translate emissions from a microscopic level to a macroscopic level. At a microscopic level, the emission data are obtained on a second-by-second basis while a vehicle's emissions are quantified. At a macroscopic level, if the total vehicle emissions are required, the driving conditions in the study area need to be recognized allowing the total emissions to be calculated by combining the data of individual vehicles' emissions based on their particular driving conditions. Driving cycles are the bridges between the driving conditions and characteristics of individual vehicles and the total vehicle emissions.

1.3 Status of Current Research

1.3.1 Existing Driving Cycles

Several driving cycles have been developed in different countries to represent their typical driving conditions. The first driving cycle based on the FTP was created in the late 1960s to comply with federal standards (Austin, et al., 2003). The cycle was used for both vehicle certification and emissions inventory development. In the early 1990s, the CARB created another standard cycle, the Unified Cycle (UC) for estimating mobile source inventories in California. Since then, the United States EPA has also created a number of new cycles reflecting specific levels of service (LOS) and facility types (e.g., freeways and arterials) (Carlson & Austin, 1997).

European driving cycles were prepared by the Economic Commission for Europe (ECE) and the European Economic Community. Since 1992, the Extra Urban Driving Cycle (EUDC) was added to previous cycles to represent rural driving conditions. Then, two cycles were combined (ECE+EUDC) and referred to as the New European Driving Cycle (NEDC). In Japan, the 10-15 mode cycles are currently used for emission certification and fuel economy estimation for light duty vehicles. Besides these widely accepted driving cycles, there are numerous other driving cycles such as the ADC (Tzirakis, et al., 2006), INRETS commercial vehicles driving cycles (France), the Perth driving cycle (Australia) (Esteves-Booth, et al., 2002), and the "TEH_CAR" cycle (Iran) (Montazeri-Gh & Naghizadeh, 2003), etc.

More information about these existing driving cycles will be provided below in Chapter 2, the Literature Review.

1.3.2 Current Methodology for Developing Driving Cycles

The general method for developing driving cycles today is to first collect typical driving data from the real world driving situation and then construct the cycle by dividing the collected speed-time traces into smaller sections termed microtrips (Lin & Niemeier, 2003). A microtrip is defined as a portion of the speed-time trace of driving with boundaries of idle mode (zero speed) at either end. These microtrips are then combined into various groups. The groups represent collections of similar traffic conditions (e.g., average speed) and/or facility types (e.g., freeway and arterial). After data have been classified into groups, microtrips are chosen according to certain criteria (sometimes randomly) and then are spliced together to form a complete driving cycle. The basic logic in choosing microtrips is to ensure that they closely replicate the trend and characteristics of the entire driving data set. The final step requires a single cycle to be selected from among the generated candidate driving cycles based on a set of target statistical measures, such as average and maximum speed and acceleration, percent idle, a measure of acceleration work (Watson, et al., 1982), and joint speed-acceleration frequency distribution (SAFD) sometimes referred to as a Watson plot (Austin, et al., 2003; Milkins & Watson, 1983). Figure 2 provides a general flowchart of the current methodology used to develop driving cycles.

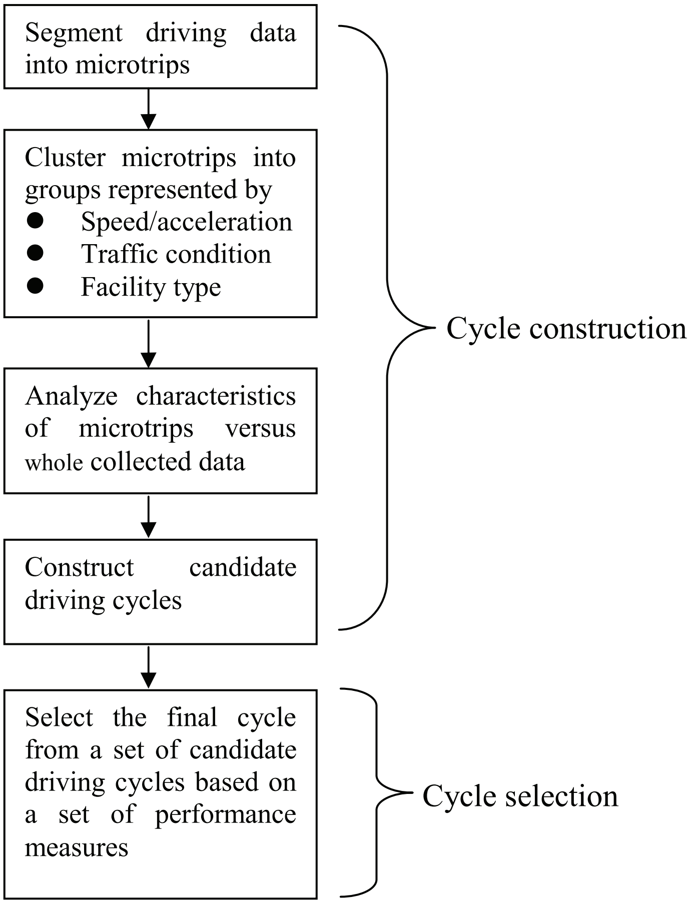


Figure 2 Current Driving Cycle Generation Process

1.3.3 New Technology in Data Collection

The development of existing driving cycles has not incorporated emission characteristics, mainly because no technology was available to collect second-by-second emission data in a real scenario on the roads. Existing data collection technologies are not capable of supporting the development of driving cycles that capture emission characteristics. A new technology, called the Portable Emission Measurement System (PEMS), has been under development for about a decade and has now changed this limitation by providing a unique approach for collecting real-time emissions as well as driving activity data that are both essential for the development of new generation driving cycles. The source data for the FTP and California driving cycles were respectively collected in the 1960s and early 1990s when PEMS was not yet available. Until as recently as 2006, onboard electronic equipment, such as Global Positioning System (GPS), On-Board Diagnostic (OBD) System II reader, and accelerometer were relied upon in the development of ADC. Furthermore, PEMS was not available in the developments of other driving cycles, such as the French commercial vehicle driving cycles, Australian Perth driving cycle, and "TEH_CAR" that is an exclusive driving cycle developed for the city of Tehran, Iran. In fact, PEMS has not been comprehensively applied in the development of driving cycles so far.

1.3.4 Problems of Current Research

The existing methodology for developing driving cycles only incorporates information about a vehicle's driving activities, such as average speed, maximum speed, and the proportions of different driving conditions and does not consider emission characteristics, although the resulting driving cycles are in many cases intended to evaluate emissions. It has long been acknowledged that the FTP does not adequately reflect normal on-road driving patterns (Niemeier, et al., 1999). Several driving cycles used in the MOBILE emission factor model are now considered redundant (Frey & Zheng, 2002). Since the quality of driving cycles cannot be assured, some questions have been raised in the application of the driving cycles. It is commonly agreed today that similar driving conditions may sometimes produce totally different emission characteristics. As a simple example to illustrate this phenomenon, many researchers have shown that significantly different emission rates can result from the same average speed (Trozzi, et al., 1996; Joumard, et al., 1995; Hansen, et al., 1995; Andre & Proncilo, 1997). Therefore, it is inadequate to take only driving activities into account in the development of driving cycles. Previous driving cycles were clearly developed with the objective to match emissions with the speed profile, without considering the impact of driving conditions upon emissions at the same time. If the purpose of developing driving cycles is to evaluate vehicle emissions for the purpose of either air quality inventories or emission controls, the emission characteristics should be a primary factor of development of driving cycles. The speed profile is related to emissions but cannot represent emissions completely. In other words, not only should the developed driving cycles be a reflection of speed profiles under real world driving conditions, but the emission characteristics should also accurately reflect actual conditions.

In addition to the consideration of the approach used in the development of an effective driving cycle, how far driving cycles can actually represent a real world driving situation of vehicles depends on the availability of an effective and comprehensive evaluation method that is able to assess the developed driving cycles. Such an evaluation method is not yet available.

1.4 Objectives of Research

In light of the above discussions, the goal of this research is to help reduce vehicle emissions and improve the air quality. To this end, the objectives of this research are threefold.

1. Propose a new methodology for developing driving cycles considering both driving conditions and emission characteristics, and then apply it to develop driving cycles for light duty gasoline vehicle (LDGV) for classified roads. This will be achieved by using a comprehensive emission and driving database collected by PEMS, which stores abundant on-road emission and driving data.

2. Develop a VSP-based evaluation method for driving cycles, which will be applied to compare the driving cycles developed by the methodology of this research with other driving cycles developed by existing methodology, with the aim of demonstrating the significance of incorporating emission characteristics in the development of driving cycles.

3. Apply the developed driving cycles to the IVE model to estimate emission factors for the study area.

CHAPTER 2: LITERATURE REVIEW

As discussed in Chapter 1, there have been numerous studies on driving cycles. In order to fully understand the nature of this important research, a comprehensive literature review has been conducted. This chapter will summarize existing studies in a number of research areas associated with driving cycles and will include the following.

First, some of existing driving cycles that are widely used in United States, Europe, and Japan are reviewed in order to provide the status quo of this important research topic.

Second, several main methods for emission measurements are presented. The techniques and features of the equipment employed to collect emissions are critical to the quality of data source.

Third, different methodologies related to the development of driving cycles are reviewed in detail. Their pros and cons are then discussed.

Based on the literature review of existing driving cycles, specific problems in the existing research are highlighted.

Finally, different schemes and plans for conducting the data collection tests are presented.

2.1 Existing Driving Cycles

Almost all developed countries have released regulations to reduce vehicle emissions, because there are different political and economic systems, and levels of technology regulations are different in each country. Different regulations inspire different motivations about the aims of driving cycle research. Presently, the United States, Europe, and Japan are the three main countries where advanced research is being conducted on driving cycles.

There are two types of driving cycles: transient driving cycles and modal driving cycles.

Transient driving cycles involve many changes such as frequent speed changes during typical on-road driving. Modal driving cycles involve protracted periods at constant speeds. This means that there are parts in these cycles where the speed is constant. The parts in transient cycles at which the speed is constant are much shorter than those in modal cycles.

2.1.1 United States Driving Cycles

The United States driving cycles belong to the transient type. The first driving cycle based on the FTP was created in the late 1960's to comply with federal standards (EPA, 1993). The cycle was used for both vehicle certification and emissions inventory development. FTP-72 was developed in 1972 based on test data collected from passenger cars in the morning in the city of Los Angles. After 1975, FTP-72 was amended to FTP-75.

Figure 3 shows a speed time trace of FTP-75.

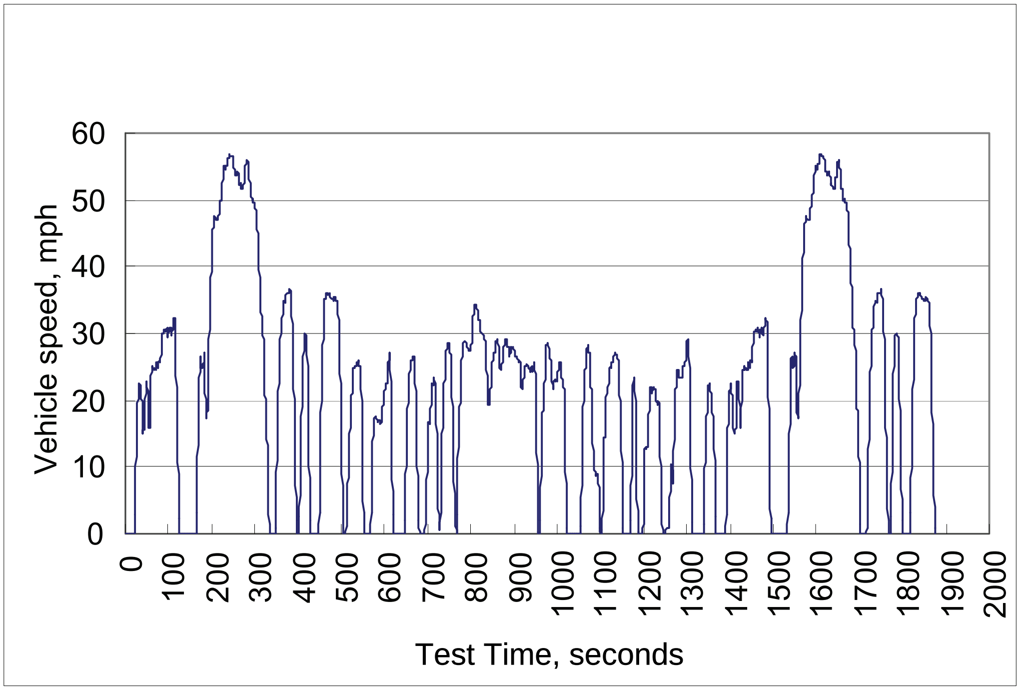


Figure 3 Illustration of the FTP-75 Driving Cycle

Speed Data Source: Ecopoint Inc., 2007.

The FTP-75 cycle is derived from the FTP-72 cycle by adding a third phase of 505 seconds, identical to the first phase of FTP-72 but with a hot start. The third phase starts after the engine has stopped for ten minutes. Thus, the entire FTP-75 cycle consists of the following segments: (1) cold start phase (0~505 seconds), (2) transient phase (506~1372 seconds), and (3) hot start phase (1373~1877 seconds). The speed trace of the third phase is equal to the first phase. The SFTP was developed to address the shortcomings in the FTP-75 test cycle in the representation of aggressive, high speed and/or high acceleration driving behavior and rapid speed fluctuations.

In the early 1990's, CARB created another standard cycle, UC, for estimating mobile source inventories in California. Since then, the EPA had also created a number of new cycles reflecting specific levels of service (LOS) and facility types (e.g., freeways and arterials) (Carlson & Austin, 1997).

2.1.2 European Driving Cycles

European Driving Cycles belong to the modal driving type, which simply consists of constant speed and constant accelerations, not like transient driving cycles such as that in the United States. This is modeled by FTP which has variations in speed and acceleration on a second by second basis. The European driving cycles were prepared by the Economic Commission for Europe (ECE) and the European Economic Community. The early European driving cycles were a simple representation of the driving pattern in the city only and were composed of fifteen driving conditions, and thus were called the ECE15. Since 1992, the Extra Urban Driving Cycle (EUDC) was added on to the previous cycle to represent rural driving conditions. The two cycles were then combined (ECE+EUDC) and referred to as the New European Driving Cycle (NEDC) (Tzirakis, et al., 2006) as shown in Figure 4.

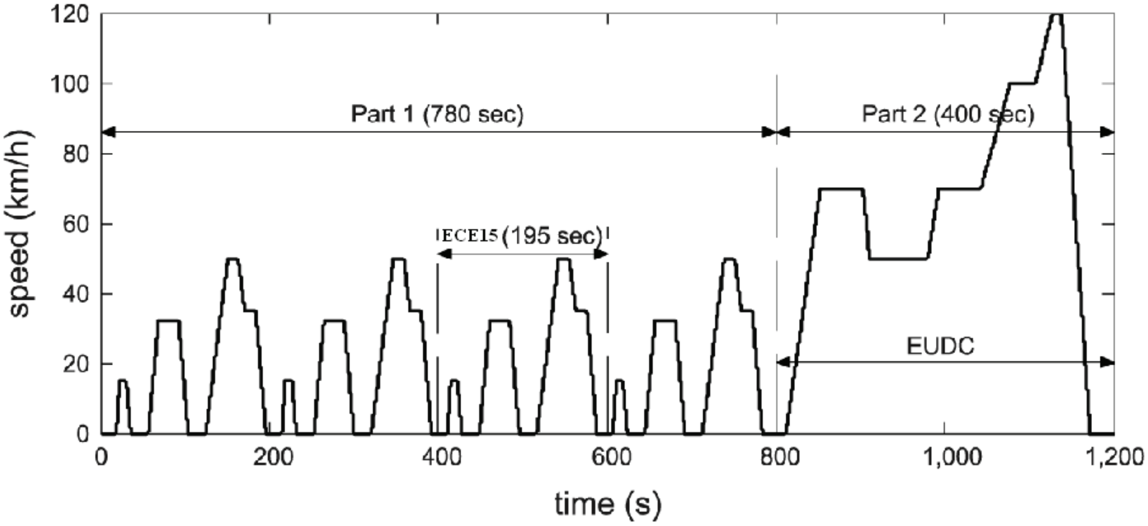


Figure 4 Illustration of NEDC Driving Cycle

Source: Mester, 2005

2.1.3 Driving Cycles in Japan

Driving cycles in Japan are simple and also belong to the modal driving cycle category.

The 10 mode cycle (JISHA, 1983) was used for emission certification of light duty vehicles in Japan. The 10 mode cycle simulates urban driving conditions. Constant volume sampling was used to collect exhaust emissions during the test.

The 10-15 mode cycles are currently used in Japan for emission certification and fuel economy testing for light duty vehicles. It is derived from the 10 mode cycle by adding another 15-mode segment of a maximum speed of 70 km/h. It features three 10 modes and one 15 mode. Figure 5 shows the Japan 10-15 mode cycle.

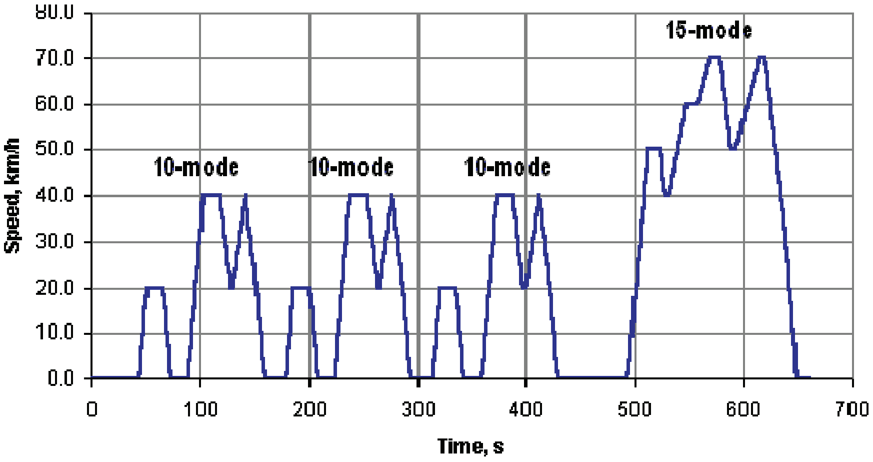


Figure 5 Illustration of Japan 10-15 Mode Driving Cycle

Source: Ecopoint Inc., 2007.

2.1.4 Other Driving Cycles

Besides the above widely accepted driving cycles, there are numerous other driving cycles.

The ADC. ADC stands for Athens Driving Cycle. Differences from other European cities and the rapidly changing traffic conditions as well as the expanding transportation network and the atmospheric pollution problems in Athens, Greece imposed the need to develop the ADC. Onboard electronic equipment[s (e.g., GPS, OBD II reader, accelerometer, etc.) were used and on-road traffic data were collected, covering almost all of the Athens road network over a two year period. Dedicated software was developed for the statistical analysis of the recorded parameters (Tzirakis, et al., 2006).

The European Driving Cycle (Inter-European project). European researchers at Volkswagen have analyzed the option of adapting the previously mentioned cycle (United States FTP-75) to European traffic conditions. To obtain a comparison between the European and American situations, vehicles were instrumented by various car manufacturers and real driving measurements were performed on seven road routes (in Torino in Italy, Versailles in France, London in the United Kingdom, and Stuttgart in Germany). Drivers were given instructions such as "normal driving style" and in a number of cases, "gentle" or "aggressive" driving styles. The data were analyzed to enable a comparison to be made of parameters such as stop frequency and duration and trip length (Andre, 1996).

German Motorway Driving Cycle. Experiments were conducted on a large scale, with the view to developing motorway driving cycles, assessing the exhaust emissions generated and understanding the influence of speed limitations on emissions generated. A set of cycles was derived using the "Monte Carlo" statistical method and acceleration was simulated from speed versus time as a function of the cumulative distribution of acceleration for each considered speed level. As a result, various driving cycles were constructed according to one to three speed levels, two desired speed ranges (100 km/h and 130 km/h), four classes of traffic conditions (based on traffic density), and three gradient levels and vehicle types (Andre, 1996).

"TEH_CAR" Cycle. "TEH_CAR" cycle was developed to simulate vehicles' exhaust gas emissions and fuel economy in the city of Tehran, Iran. An on-road test for the city of Tehran was performed and speed data were collected. The car speed was recorded in city traffic conditions. Based on the analysis of the recorded data, a driving cycle was developed. Applying the statistical analysis, the cycle was then modified and a real world smoothed cycle was developed (Montazeri-Gh & Naghizadeh, 2003).

2.2 Vehicle Emission Measurement Methods

Measurement of vehicle emissions is required for quantification of vehicle emission, and the measured data also provide the basis for the evaluation and control of vehicle emissions. It is also sometimes employed for the application or the development of driving cycles, especially when emissions are a primary factor in the evaluation of driving cycles. The research in this report requires the use of emission measurements in the development of driving cycles.

Currently, there are four main emission measurement methods: Chassis Dynamometer Test, Tunnel Test, Remote Sensing, and PEMS.

2.2.1 Chassis Dynamometer Test

This method combines the chassis dynamometer with the emission analyzer and control computer. The test vehicle runs on the chassis dynamometer according to a road simulation from the computer in order to quantify this vehicle or more accurately this engine's emission factors based on the test vehicle's exhaust during the test. The driving pattern simulated by the computer in the test is the driving cycle. Accuracy of the test results depends mostly on the quality of driving cycles. In fact, the chassis dynamometer test is not intended to develop driving cycles but instead to apply the driving cycle for the measurement of emissions. Therefore, the chassis dynamometer test is not applicable to the development of driving cycles.

2.2.2 Tunnel Test

This method collects emission data in a tunnel and applies the pollutant diffusion model to deduct individual emission factors according to pollutant concentration from the fleet in the tunnel, wind speed in the tunnel, and other environmental factors. Emission factors derived from this method can represent the emission levels for a real driving pattern of the fleet in the tunnel. However, the driving pattern in the tunnel is so different from the normal driving pattern that the limitation of this method is clear. For that reason, the test data from the tunnel test cannot be considered as completely representative of actual real world driving conditions. The data cannot be used for developing driving cycles either.

2.2.3 Remote Sensing

This method is a technique applied in United States and some other countries after the 1990s. This method can accomplish the test at a specific site during the vehicle's normal driving. The characteristics and benefits of this approach are automation and efficiency. Nevertheless, the method imposes very strict requirements on the traffic situation and test locations and can only test concentrations of exhausts, which means that the mass of the emission cannot be obtained. Therefore, remote sensing does not meet the requirements of the data source for driving cycles due to the nature of the data.

2.2.4 Portable Emission Measurement System (PEMS)

This is the advanced emission test method applied after 2000s. It overcomes the problem that the chassis dynamometer in the lab cannot properly simulate driving patterns in the real world. Furthermore, it can easily collect the emission data on diverse roadways, during different time periods, and from various types of vehicles without the limitation of the remote sensing technique. Montana OEM-2100 (CAT, 2003), consisting of emission analyzers and a built-in computer system, was developed by Clean Air Technologies International, Inc. (CAT) and is one of the most advanced PEMS able to collect engine data, vehicle speed, acceleration, concentration and mass of emissions, and fuel consumption on a second-by-second basis. The research in this report is based on data collected by Montana OEM-2100.

2.3 Methodologies for Development of Driving Cycles

After the data is collected, the development of driving cycles can commence. From a review of the literature it is seen that many methods have been used to synthesize a driving cycle in the past. Most of them can be classified in these three groups (Alessandrini & Orecchini, 2003): Extrapolation Method, Selection Method and Simulation Method.

2.3.1 Extrapolation Method

This method is used to design the standard homologation cycles. The acceleration phases are all at a constant acceleration and the average parameters of the cycle (average percentage of time in idle mode, speed range intervals, etc.) are reproduced repeatedly. In other words, the synthetic cycle’s operational modes are smoothed into phases of steady speed and acceleration. Examples of such cycles are the ECE European cycle (Ecopoint, 2007), Japanese 10-mode cycle (JISHA, 1983), etc. The cycles so obtained are very easy to follow by a car on a chassis dynamometer but are not really representative of the real driving conditions.

2.3.2 Selection Method

This method selects a few representative time-speed sequences regarding certain common summary characteristics of the data collected. The sequences are linked by idle phases. The key to this method is the definition of the microtrip. Microtrips are defined as segments of speed data that begin and end at rest with at least two consecutive seconds of zero speed. The representative microtrip is the one that minimizes the difference between its parameters and those of the whole/complete data in a certain category of traffic conditions. The concept of this method was widely accepted for developing driving cycles. The method to develop FTP is to splice together segments of real speed patterns (i.e. microtrips) that are selected from the survey data. A final cycle is obtained by matching summary features of the resulting speed-time trace with those of the full sample (EPA, 1993). An instance where the Selection Method was employed is by CARB to produce the UC in 1992 and then the new Unified Correction Cycles (UCC's) too were developed using the Selection Method (Gammariello & Long, 1996). This method is relatively superior and a more popular choice for developing driving cycles (Lin & Niemeier, 2003).

2.3.3 Simulation Method

This method uses all the collected data to synthesize a statistically representative driving cycle by tracking a path through a joint speed–acceleration matrix. It uses random number generation to simulate the probability component in which a time sequence of speeds is produced with characteristics. A driving cycle for electrically-driven vehicles in Rome, Italy (Alessandrini & Orecchini, 2003) and a German motorway driving cycle (Esteves-Booth, et al., 2002) were generated using this method, simulating acceleration from speed versus time as a function of the cumulative distribution of acceleration for each considered speed level. This method is likely to be a more efficient method in producing different cycles, but these cycles are wholly "unreal" in comparison to the Selection Method described above and have the potential of yielding driving segments that could arguably be unrealistic (EPA, 1993). This raises the fear that a simulated cycle may not be drivable or, in emission testing, may yield emissions that do not or cannot occur in real driving.

2.3.4 Other Approaches

There are a few other methods that do not belong to above categories. An approach, devised in 1989, used a cluster analysis to bin all of the microtrips prior to combining them into cycles (Crauser, et al., 1989). This approach produced a cycle where every single microtrip selected was generally alike. However, this approach would tend to miss extreme driving episodes (Gammariello & Long, 1996), and since extreme driving conditions will give out significant emissions these should not be omitted.

Besides microtrips, facility specific cycles were designed in 1989 for freeways and arterials using a snippet approach (Effa & Larsen, 1989). A snippet is a change in traffic density for a given freeway or a change in the physical link to or from an area transportation network. By breaking up the microtrips into snippets and then rejoining them, artificial acceleration/deceleration episodes could be identified (Gammariello & Long, 1996) which greatly affected the emission estimate.

In summary, the Selection Method is a relatively more comprehensive, advanced, and commonly accepted methodology for developing driving cycles.

2.4 Problems Identified in the Existing Research

A number of problems have been identified during a review of literature on existing research on driving cycles. The problems are summarized as follows.

2.4.1 The Limitation of Source Data

Plentiful, comprehensive, and accurate source data collected from a field test in the real world are the basis for making any driving cycles applicable and representative. Most existing driving cycles were developed based on early field tests that were not broad and ample enough, and were unable to represent the evolving traffic situations in cities. Therefore, the old test data were incapable of providing a basis for developing new driving cycles.

2.4.2 A Lack of Classification of Driving cycles

Different emissions result from the use of dissimilar roadways on which different driving characteristics are found, for different driving time periods, and for various loads that the vehicles carry. Although most of driving cycles are grouped into rural and urban categories, there is a lack of driving cycles that are categorized by facility types.

2.4.3 A Lack of Incorporation of Emission Characteristics in the Development of Driving Cycles

Only a limited range of driving activity parameters in the test data, such as speed, acceleration and proportion of different driving modes, were utilized in the development of earlier driving cycles. Emission characteristics were omitted. If the objective of developing driving cycles is to evaluate vehicle emissions for the purpose of either air quality inventories or emission controls, then the emission characteristics are indispensable.

2.4.4 A Lack of Effective Evaluation Method for Driving Cycles.

The method used to evaluate the quality by which driving cycles represent real driving situations is very important in developing driving cycles. However, there has been a lack of effective methodology to evaluate driving cycles developed by various methodologies.

2.5 Data Collection

In addition to test devices and test plans (which include test route, test time, etc.), data collection for driving cycles has special requirement for drivers. The test vehicle cannot be optionally driven because the intent of driving cycles is to simulate the typical driving pattern, not a particular tester's driving behavior. It is observed that test drivers tend to behave differently during driving when they are aware of being tested.

Three common methods, also called protocols, (a protocol is a strategy for conducting the test) are used to eliminate the negative impacts on the testing drivers when the real-world driving activity data and the corresponding vehicle emission data are being collected. They are Chase Car Protocol, Instrumented Vehicles (IV) Protocol, and GPS Protocol (Niemeier, et al., 1999).

2.5.1 Chase Car Protocol

The main idea behind this approach is to simulate normal driving behaviors in the study area by following the target car which is a regular vehicle driven by others who do not know they are included in the tests. The chase car is an instrumented vehicle that records second-by-second data as it follows a predetermined route within a selected city. The chase car uses a laser to record the relative distance between itself and a target vehicle. With this information, it is possible to estimate second-by-second speed and acceleration data for the target vehicle. The advantage of this method is that it can simulate regular driving behaviors, but it is very difficult to chase the target car in practice. When the target car is lost, the collected data record of the tester's driving behavior shows irregular driving behavior because the tester has had to drive aggressively to catch the target car.

2.5.2 IV Protocol

In this protocol, test vehicles are selected from a pool of vehicles entering the cities' Inspection/Maintenance (I/M) stations during the study period. The driver of a vehicle that enters the designated I/M station during one of the randomly chosen time periods is invited to participate in the study. The advantage of the IV Protocol is that it is collecting driving data from sampled drivers driving their own vehicles. Disadvantages include biases that occur due to the presence of the instruments in the vehicle (i.e., the drivers know they are being monitored).

2.5.3 GPS Protocol

As the GPS device becomes more and more popular, a number of researchers are expressing interest in using GPS units to collect driving data to replace the Chase Car and IV methods. The GPS protocol can be categorized as an IV protocol, so it has several advantages and disadvantages similar to the conventional IV protocol. In addition, GPS has some other appealing advantages that are superior to the IV protocol. First, with map matching capabilities, the GPS can capture facility types on which the sampled vehicles are driven. Second, the GPS units are popular with the public and easy to install, and thus people tend to feel more comfortable with them than with conventional instrumentation.

2.6 Summary

The literature reviews of current research on driving cycles and existing technologies have resulted in a number of useful points for this research. Driving cycles are very important in the research of on-road emissions especially in the quantification of emissions. PEMS is an advanced technology that has emerged in recent years, and offers a new experimental instrument for the research of vehicle emission control as well as driving cycle development. GPS Protocol, which has advantages over the Chase Car Protocol and IV Protocol, could be applied as a guide in this study to collect driving condition data from the real world. Regarding the development of driving cycles after the data collection, the Selection Method is more comprehensive than the other methods. However, some problems are identified in the existing research. In the next chapter this study will strive to overcome these shortcomings by proposing a new methodology for developing driving cycles. Furthermore, a VSP-based evaluation method for driving cycles is also presented in the report.

CHAPTER 3: DESIGN OF THE STUDY

Based on achievements of existing research and problems highlighted by the literature review in Chapter 2, the methodology of this study is designed for achieving the objectives determined in Chapter 1, namely, developing an emission characteristics-based approach to develop driving cycles, developing VSP-based method to evaluate driving cycles, and applying the developed driving cycles for emission estimation. The general process of the research consists of five stages.

The first stage is a comprehensive review of existing literature on driving cycles to identify research problems, based on which the study objectives aimed at solving these problems are identified. This stage was carried out in Chapter 2.

The second stage is the preparation of data source. Data collection is a critical step for the research. This study proposes to use the data collected by Beijing Jiaotong University (BJTU), Beijing, China. We use the data collected in Beijing because there is a large amount of available test data. In addition, those data have gone through a pre-processing which provided a solid foundation for the development of the proposed approach for developing driving cycles in this study. A series of tests were conducted using PEMS for various types of vehicles on different facility types between the years 2004 and 2006, and then the collected data were processed and stored in a database. Although the collected data are utilized as the data source to develop driving cycles in this research, not all collected data fit this study. Because the target vehicle type is light duty gasoline vehicles, the task is to select and retrieve an appropriate data set from the database and to classify the selected data into the four groups that are required by this research.

The third stage is the core of this research. This stage is to process the data obtained in the second stage and then to develop the driving cycles. The general procedure of the proposed methodology is to follow the Selection Method, which is to abstract portions of data and then to combine them into driving cycles. Six steps are incorporated in this stage to achieve the objective, which is to develop driving cycles that can better represent not only the driving pattern, but also emission characteristics when vehicles are being driven. In order to overcome the shortcomings of existing methodology, both activity and emission measures are incorporated in the development of driving cycles. Several candidate driving cycles are developed during this stage, and a final driving cycle will be created/produced in the next stage.

The fourth stage is the evaluation of the driving cycles. A new evaluation methodology based on VSP is presented. Sensitivity analysis is performed in order to reveal the reasons why VSP is chosen as criteria to evaluate the quality of driving cycles. Essentially, the methodology evaluates how well the driving cycle represents the driving conditions for vehicles in the real world. In this stage, two different sets of driving cycles are developed. One is developed using the proposed methodology; and another one is developed by a modified version of the methodology which represents an existing methodology. A comparison between these two sets of driving cycles is carried out to illustrate/discover which one is better.

The last stage utilizes the IVE model to estimate emission factors based on the driving cycles developed by the proposed methodology. This is the application stage, because the emission estimation is one of the important applications of driving cycles.

Accordingly, Figure 6 shows the sequence and relationships of these five stages. The development of driving cycles is a systematic procedure with many related steps. This report starts with the literature review about driving cycles, which is followed by a presentation of an emission characteristics-based methodology used to develop better driving cycles, and then the evaluation of the developed driving cycles by means of VSP is introduced. Finally, the application of the developed driving cycles is presented.

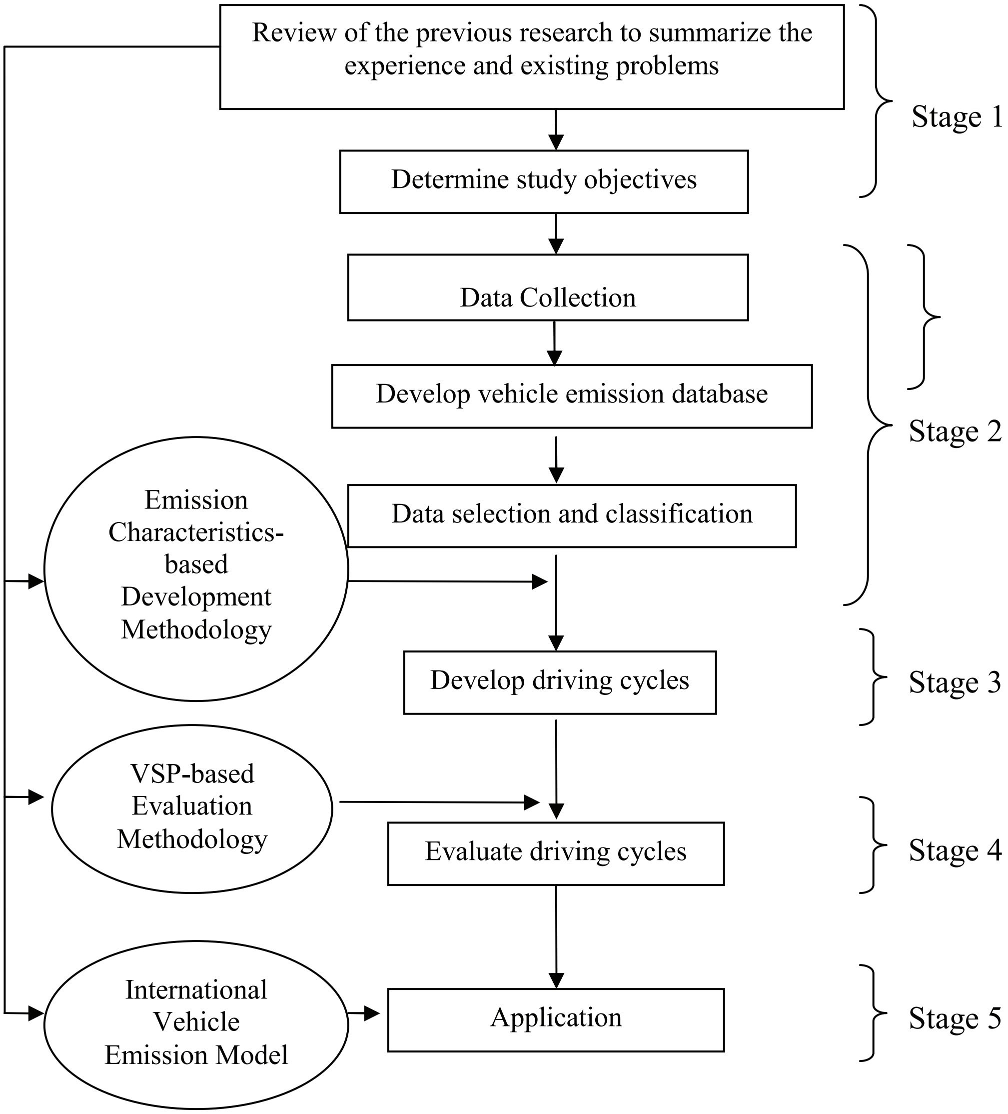


Figure 6 Diagram of the Study Method

CHAPTER 4: RESULTS AND DISCUSSION

This chapter of the report strives to present the particular steps undertaken to achieve the objectives of the research. It then summarizes the results and findings from the research. Full and specific tabular information as well as figures are provided to facilitate the discussion of the results.

4.1 Data Source

The data source is a fundamental element of this research and is therefore the key to ensuring the quality of the developed driving cycles. The specialized emission tests are requisite to establish the exclusive data source required for creating the driving cycles in this research. The data collection requires a superior device, a comprehensive test plan that covers various test vehicles and test roadways, and dedicated testers who can strictly stick to the pre-designed guidelines to perform the tests.

In this study, the data collection was conducted by the scholars and students at BJTU. They pre-processed the collected data and stored them in a database which is utilized in this research to develop driving cycles. Because the quality of the data source has a direct influence on the effectiveness of the proposed approach for developing driving cycles, it is necessary to present the details of the data collection plan even though those works were not directly conducted by the authors of this report. Detailed data collection plan includes a description of the study area, test devices that were employed in the data collection, data collection protocol, the procedure of performing data pre-processing, and the source data selection method.

4.1.1 Study Area

The data were collected in the city of Beijing, China. The most important reason of using Beijing data is that there is a huge amount of vehicle activity and emission data that can be readily used to develop driving cycles according to the proposed approach in this research. In addition, those available data have been pre-processed, which is very helpful to ensure the quality of the developed driving cycles. The transportation environment lab at BJTU purchased a Montana OEM-2100 in 2003. Since then, a series of data collection activities have been conducted. The accumulated data are sufficiently large and of such a high quality that it would be hard to find in most other places.

4.1.2 Test Devices

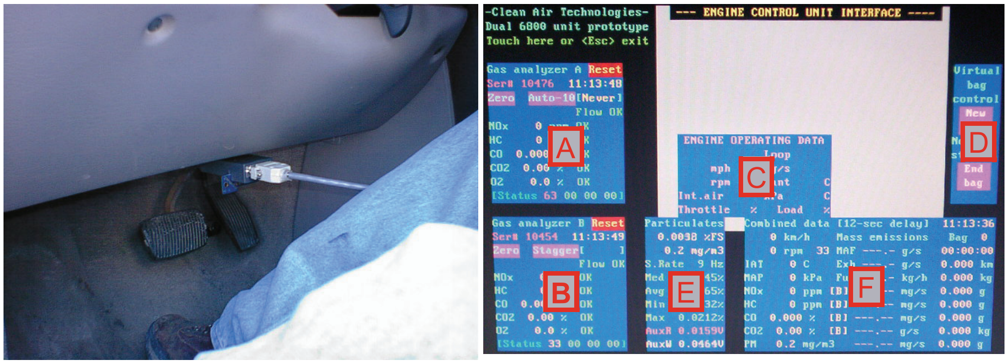
There are several emission test technologies and devices that could be used to collect vehicle emissions as discussed before. However, only PEMS fits the requirements of this study according to the findings from the literature review. The GPS device is also useful, since it is able to provide the vehicle's speed and position information that is helpful in the data preparation. Therefore, PEMS and GPS devices were used to collect the data.

PEMS. The Montana OEM-2100 device was utilized to collect the data. It is an advanced PEMS manufactured by CAI, designed to measure vehicle mass exhaust emissions under actual on-road driving conditions using vehicle and engine operating data and concentrations of pollutants in exhaust gas sampled from the tailpipe. It is designed to provide instantaneous HC, CO, carbon dioxide (CO2), NOx, and O2 readings for gasoline-powered vehicles and HC, CO, CO2, NOx, O2, and PM (light scattering) readings for diesel vehicles. In addition to collecting instantaneous emissions, OEM-2100 can also record engine parameters including the vehicle speed via the vehicle OBD II interface. All the data that OEM-2100 is able to collect is indispensable to the research in this research.

The OEM-2100 unit may be placed in or on the test vehicle. For in-vehicle installation, the exhaust sample lines can be routed through a window and secured to the exhaust system using hose clamps. The power is drawn from a cigarette lighter outlet or from a cable clamped directly onto the battery. The unit is secured by adjustable tie-down straps. Figure 7 displays a selection of pictures taken during the test conducted with the OEM-2100.

OEM installed in the test vehicle

Exhaust sample lines secured to the exhaust system using hose clamps



OEM connected to the vehicle's Computer via OBD II interface

The operation interface on the screen

Figure 7 Selected Pictures of OEM during the Test

GeoLog GPS device. The GeoLog GPS receiver was used to collect the global position and speed information of the test vehicle as well as the exact corresponding time on a second-by-second basis. It was placed inside the instrument-fitted car and fixed under the front windscreen where there was no blockage to interfere with the signal from satellites.

By linking both the OEM-2100 and the GPS devices with an accurate timer as the frame of reference, the correspondence between the vehicle emission data set and the real driving condition data set was built up to record the vehicle's geographic position, the driving condition information, and emission data on a second-by-second basis. The OEM-2100 provides the useful function of "Bag Control" that allows the instrument operator to tag the data output file for particular test stages and to create corresponding summary reports (CAI, 2003). The software of OEM-2100 integrates the distance, fuel consumption, and emissions over the duration of each "bag," and reports this summary at the end of the test and exports it to an output file. With the help of this function, the representative driving condition information and corresponding emission data information were collected and recorded.

Both PEMS and GPS were employed to collect the instantaneous vehicle activity data, such as speed, acceleration and deceleration, and emission data, such as NOx, HC, CO, etc. After the data collection, the data pre-processing was completed to provide a specific database in which each record included the activity and emission information for every second.

4.1.3 Data Collection Plan and Conduct Protocol

The data collection was performed on different types of vehicles and a variety of testing routes (freeway/expressway, principal arterials, minor arterials, and local streets). In addition, the testing vehicles are at various ages, kilometer ages (total kilometers traveled during a specific time period, such as a year), and use different fuel types. The collected data included: emission data (CO, CO2, HC, NOx, and PM), fuel consumption data, vehicle activity data (speed, acceleration, rpm, etc), and GPS data. Furthermore, the tests spanned different dates and time periods. A total of 52 vehicles were used in the data collection process covering 58 days during the period of 2003-2006. The tested vehicles included light duty gasoline vehicles (LDGV), heavy duty gasoline vehicles (HDGV), light duty diesel vehicles (LDDV), and heavy duty diesel vehicles (HDDV). There were 34 LDGVs tested which accounted for 65.4 percent of all vehicle types. In order to minimize the influence of individual drivers' driving behavior, 51 different drivers were employed throughout the tests. The testing routes selected covered various road types and the tests were conducted during different time periods between 8:00 am to 8:00 pm (most of the tests were conducted between 10:00 am and 2:00 pm). These tests were conducted on four classes of roadways: freeway or expressway, principal arterial, minor arterial, and local streets (Qiao, et al., 2007).

The driver of the instrumented car was instructed to follow the motion of a specific type of vehicle during each test run to simulate the driving patterns of the target car, which is in line with the chase car protocol (Niemeier, et al., 1999). In order to remedy the shortcomings of this protocol, tests were repeated using the same route more than one time. This method was designed to collect similar and comparable data. Repetition will effectively eliminate sampling errors.

4.1.4 Data Quality

A data quality assurance procedure was used to ensure that only valid data would be used for subsequent application. Under bridges, high buildings or heavy clouds, the GPS will lose its signal, which results in data losses or random errors. When data are lost, an interpolation is applied, which fills in the gaps, according to the data trend. If the data gap is longer than five seconds, the related data would be removed. In addition, GPS-based data were compared with the OEM-based speed data to check and fix abnormal records resulting from random errors. Therefore, a combination of speed data from two different sources ensured a reasonable level of data accuracy.

Data loss and random errors occurred during the data collection by OEM-2100, mainly due to a temporary device failure caused by rough roads. The invalid data were found to represent less than five percent of the collected data. A dedicated program was used to eliminate those invalid data.

4.1.5 Database of the Collected Data

After the data processing, the collected data were stored in a database developed using Microsoft ACCESS 2003. There are five tables in this database. One is the EMISSION table that stores vehicle emissions, fuel consumption and other vehicle parameters. Appendix B presents the structure of EMISSION table which is the most important table in the database. Another table is named BAG which recorded bag information. The third one is the VEHICLE table that stored tested vehicles' information. The fourth one is the WEATHER table that recorded weather information. The last one is the DRIVER table that stored information on the driver who drove the test vehicle.

More specifically, the EMISSION table stored second-by-second test data including time, speed, acceleration, NOx, HC, CO, etc. The information for each second was stored in one row. The BAG table stored bag summary information including test date, bag file name, bag number, entry time, road name, etc. The VEHICLE table stored test vehicles' information and test road information, such as vehicle maker, engine information, year manufactured, kilometerage, street name, and roadway type. The WEATHER and DRIVER tables included temperature, humidity, gender of driver, age of driver, etc. Even though the information in VEHICLE, WEATHER, and DRIVER tables did not directly come from test devices they proved to be very useful for the present study.

These five tables are interconnected. For example, if the second-by-second test data of 2003 Jetta CI (Jetta CI's maker is VOLKSWAGEN) is needed, relevant data can be retrieved according to the test date from all of five tables.

4.1.6 Selection of Data Source

One driving cycle can only represent the driving pattern of one type of vehicle driving on a certain facility type, because the driving pattern and relevant emissions vary significantly for different types of vehicles and on different types of facilities. In this study, LDGV is the target. The main reason of selecting LDGV for developing driving cycles in this context is that the database contains much more test data on LDGV than on any other types of vehicles.

The Structure Query Language (SQL) technique was utilized to select the appropriate data set from the database. SQL is the most popular computer language used to create, modify, retrieve, and manipulate data from relational database management systems. SQL allows users to access data in relational database management systems, such as Microsoft Access (Bowman, 2001). The data collected about LDGV provides an appropriate data set for this research. Table 1 illustrates the selected LDGVs whose test data are utilized in this study. Most of the test vehicles are in commercial use such as taxis, and therefore the kilometer ages vary widely.

Table 1 List of the Selected Test Vehicles

No.	Date	Model	Kilometer Ages	Age (years)	Displacement (Liters)	Fuel
1	4/4/2003	Jetta CI	46000	2	1.6	Gasoline
2	8/16/2003	Jetta CI	59934	2	1.6	Gasoline
3	9/2/2003	Xiali	N/A	4	1.0	Gasoline
4	12/19/2003	Jetta CI	141341	3	1.6	Gasoline
5	12/20/2003	Jetta CI	141341	3	1.6	Gasoline
6	12/26/2003	Jetta CI	108196	3	1.6	Gasoline
7	2/26/2004	Jetta CI	319182	4	1.6	Gasoline
8	3/2/2004	Jetta CI	398068	4	1.6	Gasoline
9	3/9/2004	Jetta CI	165892	2	1.6	Gasoline
10	3/11/2004	Jetta CI	166590	2	1.6	Gasoline
11	3/30/2004	Jetta CIX	21106	1	1.6	Gasoline
12	4/1/2004	Jetta CI	398068	4	1.6	Gasoline
13	4/8/2004	Jetta CI	172000	3	1.6	Gasoline
14	4/15/2004	Jetta CI	212512	4	1.6	Gasoline
15	4/19/2004	Fukang 988	75381	3	1.4	Gasoline
16	4/20/2004	Xiali	372823	5	0.96	Gasoline
17	5/20/2004	Xiali	30169	4	0.96	Gasoline
18	5/26/2004	Fukang	516928	6	1.4	Gasoline
19	6/3/2004	Fukang	301825	2	1.4	Gasoline
20	6/9/2004	Fukang	245643	3	1.4	Gasoline
21	7/6/2004	Fukang 998	270121	3	1.4	Gasoline
22	7/8/2004	Fukang 998	152669	2	1.4	Gasoline

4.2 The Proposed Methodology for Developing Driving Cycles

After the source data is prepared, the proposed methodology in this study is applied to the source data to develop driving cycles which are able to better represent real world driving conditions in terms of both activity features and emission characteristics.

The proposed methodology belongs to the Selection Method category. The basic idea of the methodology is to extract parts of the collected data and then splice them into a speed-time trace that represents both features of real-world driving activities and emission characteristics. To this end, a total of six steps are proposed.

Step 1. Classify the data source into four groups according to facility types

With the "bag" function of PEMS, each record was tagged with the relevant test information including the types of roads. Based on this information, the data are first classified into four groups: freeway/expressway, principal arterial, minor arterial, and local streets.

Step 2. Split data in each group into microtrips in terms of speed

As described earlier in this report, microtrips are defined as segments of speed data that begin and end at rest with at least two consecutive seconds of zero speed. The end of a microtrip is marked by one second of zero speed. Any additional seconds of zero speed are included as the beginning of the next microtrip (CARB, 2007). After this step, a series of appropriate microtrips for each facility type are generated.

Step 3. Calculate activity and emission measures for each microtrip and whole/ total /complete group data

Driving conditions vary considerably during driving. A set of measures are used to represent the changes in both driving conditions and emission characteristics. These measures can be divided into two categories: the activity measures that represent the vehicle's speed and its changes; and the emission measures that represent emission characteristics during the vehicle's operation. In previous studies, only driving activities were incorporated in the process of the development of driving cycles. Formula (1) was used to measure the driving activities difference defined as ActDiff.

$$ActDiff = \sum_{i=1}^{m} \left| \frac{Ai_p}{Ai_{total}} - 1 \right| \qquad (1)$$

where A_i is the i^{th} activity measure, the subscript p means portion of data's measure, the subscript *total* means the whole group data's measure, and m is the number of activity measures.

In this step, the portion of data is the microtrip.

In the research, emission measures are involved. Formula (2) is used to calculate emission difference (*EmDiff*).

$$EmDiff = \sum_{j=1}^{n} \left| \frac{Ej_p}{Ej_{total}} - 1 \right| \tag{2}$$

where E_i is the j^{th} emission measure, the subscript p means portion of data's measure, the subscript *total* means the whole group data's measure, and n is the number of emission measures.

After definitions of *ActDiff* and *EmDiff*, *ComboDiff* is calculated by Formula (3) to represent the key measurement of vehicle emission characteristic-based approach.

$$ComboDiff = ActDiff + EmDiff \tag{3}$$

Nine activity measures are defined in the research including those which are similar to most existing methodologies:

- proportion of idling (*A1*) - (percentage)– number of idling points / total number of points,
- proportion of acceleration (*A2*) - (percentage) – number of acceleration points / total number of points,
- proportion of deceleration (*A3*) - (percentage) – number of deceleration points / total number of points,
- proportion of constant speed (*A4*) - (percentage) – number of constant speed points / total number of points,

- mean speed (*A5*) - (km/h)– sum of speeds / total number of points,
- mean driving speed (*A6*) - (km/h) – sum of speed excluding idling / number of points excluding idling,
- average acceleration (*A7*) – ($m \cdot s^{-2}$)– sum of accelerations / number of acceleration points,
- average deceleration (*A8*) – ($m \cdot s^{-2}$)–– sum of decelerations / number of deceleration points, and
- maximum speed (*A9*) – (km/h)– maximum speed in the section.

There are four emission measures in this research:

- NOx factor (*E1*) – accumulation of NOx / distance traveled,
- HC factor (*E2*) - accumulation of HC / distance traveled
- CO factor (*E3*) - accumulation of CO / distance traveled
- CO_2 factor (*E4*) - accumulation of CO_2 / distance traveled

The unit of accumulation of emission is gram and the unit of distance is kilometer. Thus, the unit of emission measure is gram/kilometer.

These measures are calculated for each microtrip and for the whole/entire group data as well. The emission measures are calculated by accumulating the emissions at each instantaneous temporal point for the subject time interval. With these measures, the relative differences between each microtrip and the whole group data could be quantified. Then, the accumulative relative differences of all measures are evaluated as the combo-difference (*ComboDiff*), which has two parts: activity part and emission part, as shown in Formula (3). In this case, m = 9 and n = 4 in Formula (3).

Formula (3) accepts that all speed measures and emission measures account for equal weight in calculating the composite differences, which are only used to select initial candidate microtrips. In selecting the final driving cycles, different weights are used according to different preferences, as shown in the following Step 6. After this step, all the microtrips are sorted in the ascending order in terms of *ComboDiff*.

Step 4. Develop the candidate microtrip pool

This step is the key step in the entire development of driving cycles in this study. In general, a 10-minute driving cycle could well be representative of a real-world driving condition; however, most researchers extend the length of the driving cycle because of the deficiency and randomness of the sampled data. On the other side, the length of a driving cycle cannot be too long, since the source data are always limited. In this research, 1,000-1,200 seconds are used as the target range in developing driving cycles. Based on the average microptrip's length, the approximate number of microtrips needed for the target length of driving cycle is determined before development of the candidate microtrip pool. All microtrips are ranked by *ComboDiff* which was described in Step 3 above, and then the microtrips with the lowest *ComboDiff* are selected as the candidates for the candidate microtrip pool. The candidate microtrip pool is a selection that contains more candidate microtrips than the numbers of microtrips that are necessary to form a particular driving cycle. In this research, the size of the candidate microtrip pool (the number of candidate microtrips in the pool) is set to 130 percent of the required microtrips (this is the number of candidate microtrips sufficient to develop a driving cycle). The extra 30 percent is based upon experiential selection and can always be changed according to practice and experience.

Step 5. Develop candidate driving cycle pool

This step picks up candidate microtrips continuously from the candidate microtrip pool until the target length (i.e., 1,000-1,200 seconds) is achieved to form the set of candidate driving cycles. Based on the tests in this research, selecting the best microtrips (with the least *ComboDiff*) strictly according to the ranked order of the *ComboDiff* measure cannot guarantee the best driving cycles. Therefore, this step generates one candidate driving cycle based on the best microtrips, while all the other candidate driving cycles are selected in a random fashion. If this operation is repeated, a large number of driving cycles could be generated. This research repeats the operation 100 times. In this way, a candidate driving cycle pool with 100 candidate driving cycles is generated for each class of facility.

Step 6. Pre-select the best representative driving cycles

A total of 100 candidate driving cycles for each facility were obtained following the Steps 1-5 above. These candidates may be similar in both activity characteristics and emission characteristics, however, the most representative one has not yet been determined. This step pre-selects the best representative driving cycles in order to reduce the selection scope to 3-5 candidates. Just as discussed earlier, there is no scientific approach to evaluating driving cycles from the emission perspective, so this step selects better ones according to arithmetical calculations. Later, a proposed method will be introduced to evaluate driving cycles as well as to select the best representative driving cycle.

This step calculates the accumulated relative activity difference (*ActDiff*) and the accumulated relative emission difference (*EmDiff*) between these candidates driving cycles and the entire group data respectively. In this step, *p* in Formula (1) and (2) represents candidate driving cycles.

The measures have the same definitions as presented in Step 3. *ActDiff* and *EmDiff* will be computed for each candidate driving cycle in the candidate driving cycle pool. Then, an indicator *Ni* is designed to represent the weighted average of the relative activity difference and relative emission difference, which is then used to select the better driving cycles. Lower *Ni* means less difference between the driving cycle and the real world data.

$$Ni = w_1 \cdot ActDiff + w_2 \cdot EmDiff \tag{4}$$

where w_1 and w_2 are the weights for the relative activity difference and the relative emission difference.

Different pairs of weights represent different levels of importance of driving activity measures and emission measures applied in the selection of better driving cycles. What needs to be emphasized is that this step simply “selects” better driving cycles. While there is no definite rule as to how the weights should be determined, five pairs of weights are used: (*1:0*), (*0.69:0.31*), (*0.5:0.5*), (*0.31:0.69*), (*0:1*), where the first number is w_1 and the second number is w_2.

The proposed evaluation method in the later part of this report provides a VSP-based approach to determine the best representative driving cycle called the final driving cycle.

4.3 Pre-selected Candidate Driving Cycles

After implementing the proposed methodology discussed above, a number of driving cycles for the four facility types were developed with reference to "*Ni*" with different weight pairs. In a real-world case, a higher activity weight means that this driving cycle has a greater similarity in driving activities to the corresponding whole group data than the driving cycle with a lower activity weight. In the sense of design, every pair of the weights selected will identify a driving cycle that can represent real world driving conditions to a certain extent, emphasizing either activity or emission or both. One weight pair will result in one candidate driving cycle. In fact, it is also possible that different weights may result in the same driving cycle. Table 2 shows a comparison of resultant candidate driving cycles for the four facility types in terms of *ActDiff* and *EmDiff*.

Table 2 Comparison of Resultant ActDiff and EmDiff of Pre-selected Driving Cycles

Weights		***(1:0)***		***(0.69:0.31)***		***(0.5:0.5)***		***(0.31:0.69)***		***(0:1)***	
Local Streets	***ActDiff.***	1.1851	(9)	1.1995	(9)	1.2564	(9)	1.2564	(9)	1.6002	(9)
	EmDiff.	1.3891		1.2816		1.2062		1.2062		1.1417	
Minor Arterial	***ActDiff.***	1.9798	(12)	1.9798	(12)	2.0364	(12)	2.0364	(12)	2.4888	(12)
	EmDiff.	0.4373		0.4373		0.3757		0.3757		0.3043	
Principal Arterial	***ActDiff.***	0.9277	(11)	0.9807	(11)	0.9807	(11)	0.9807	(11)	1.8011	(10)
	EmDiff.	0.3252		0.263		0.263		0.263		0.1581	
Freeway/ Expressway	***ActDiff.***	1.0595	(6)	1.0595	(6)	1.0595	(6)	1.2316	(6)	2.3871	(5)
	EmDiff.	0.3077		0.3077		0.3077		0.2262		0.1881	

Note: (1:0), (0.69:0.31), (0.5:0.5), (0.31:0.69), and (0:1) are weight pairs.

Each row of the facility type has two sub-rows to show the resulting values of *ActDiff* and *EmDiff*. Each column shows which weight pair is used to pre-select the candidate driving cycles. In fact, the weighted sum of *ActDiff* and *EmDiff* is *Ni*. *Ni* is used to pre-select the candidate driving cycles, while *ActDiff* and *EmDiff* are used to represent the difference of driving activities and emission characteristics between the candidate driving cycle and the entire group data. The number in the parenthesis shows how many candidate microtrips are selected to develop the candidate driving cycle. For example, the candidate driving cycle developed with weight pair (*1:0*) for Local Streets is made up of *9* candidate microtrips. This candidate driving cycle has two sub-rows indicating that its *ActDiff* is *1.1851* and its *EmDiff* is *1.3891*.

Table 2 shows that the driving cycle's *ActDiff* (i.e., the accumulated relative activity difference) is the minimum among other candidate driving cycles developed by different weight pairs, when only its activity measures are considered (i.e. weight pair *(1:0)*); while the driving cycle's *EmDiff* (i.e., the accumulated relative emission difference) is at a minimum, when only its emission measures are considered (i.e. pair (*0:1*)). All other pairs of weights generate other candidate driving cycles which have intermediate values of *ActDiff* or *EmDiff*. As yet, it is still unclear which candidate driving cycle among these pre-selected candidate driving cycles with different weight pairs is the best one (i.e., final one). Is it reliable to use the differences of driving activities and/or emission characteristics to evaluate and then determine the final driving cycle? If the answer could be yes, which weight pair is suitable for the best driving cycles? Or, is there any other weight pair which is able to achieve the best driving cycle? Another similar question is: Are the features of driving activities more important than emission characteristics? Since the driving cycles are developed in accordance with driving activities measures and emission measures, it is not appropriate to apply the same measures to evaluate the result. Therefore, a new VSP-based evaluation approach is proposed as follows.

4.4 Approach to the Evaluation of Driving Cycles

In the previous sections, no method was presented to determine how much each driving cycle represents real world driving conditions and relevant emission characteristics. In this section, an evaluation method is proposed based on the concept of VSP.

4.4.1 Definition of VSP

In 1998, Sawyer, et al. proved that there is a close relationship between emission factors and the output power of a vehicle (Sawyer, et al., 2000). Then, José Luis Jiménez introduced VSP in 1999 to describe and quantify the emission conditions during the vehicle operation (Jiménez, 1999). It includes a proportion of idling, acceleration, deceleration and cruising, and it also takes into account the effects of driving mode on emissions.

VSP is defined as the instantaneous power per unit mass of the vehicle. The units of Specific Power are those of power per unit mass. The metric (SI) fundamental unit is W/kg, which is the same as kW/Metric Ton (kW/t). The instantaneous power generated by the engine is used to overcome the rolling resistance and aerodynamic drag, and to increase the kinetic and potential energies of the vehicle. It equals the product of speed and an equivalent acceleration, which includes the effects of roadway grade and rolling resistance, plus a term for aerodynamic drag which is proportional to the cube of the instantaneous speed (Jiménez, 1999):

$$
\begin{aligned}
VSP &= \frac{\frac{d}{dt}(KE+PE)+F_{Rolling}\cdot v+F_{Aerodynamic}\cdot v}{m}= \\
&= \frac{\frac{d}{dt}\left[\frac{1}{2}\cdot m\cdot(1+\varepsilon_i)\cdot v^2+mgh\right]+C_R mg\cdot v+\frac{1}{2}\rho_a C_D A(v+v_W)^2\cdot v}{m}= \\
&= v\cdot\left[a\cdot(1+\varepsilon_i)+g\cdot grade+g\cdot C_R\right]+\frac{1}{2}\rho_a\frac{C_D\cdot A}{m}(v+v_m)^2\cdot v
\end{aligned}
\qquad (5)
$$

where:

m: vehicle mass,

v: vehicle speed,

a: vehicle acceleration,

ε_i: "mass factor," which is the equivalent translational mass of the rotating components (wheels, gears, shafts, etc.) of the powertrain. The suffix *i* indicates that ε_i is gear-dependent,

h: altitude of the vehicle,

grade: vertical rise/slope length,
g: acceleration of gravity (9.8 m/s^2),
C_R: coefficient of rolling resistance (dimensionless),
C_D: drag coefficient (dimensionless),
A: frontal area of the vehicle,
ρ_a: ambient air density (1.207 kg/m^3 at 20 °C = 68 °F), and
V_w: headwind into the vehicle.

As far as a light duty vehicle is concerned, Jose set $\varepsilon_i = 0.1$, $C_R = 0.0135$, $C_D = 0.0005$ and $V_w = 0$. Furthermore, because almost all of the tests for this research were conducted on the flat roads, the *grade* is set to 0. Therefore, the above formula is simplified to (in metric unit):

$$VSP = v \cdot (1.1 \cdot a + 0.132) + 0.000302 \cdot v^3 \tag{6}$$

4.4.2 Use of VSP Bin

Because VSP is an instantaneous parameter, in order to analyze VSP, VSP needs to be divided into bins with a certain span. In this research, VSPs are separated into a series of bins with 1.0 *kW/t* as the span. After statistical analysis of tested data, approximately 99.8% of the data's VSP values are between -20 *kW/t* and 20 *kW/t*. The meaning of each bin is the frequency (percentage) of the corresponding VSP value in the whole distribution. With this partition, the VSP distribution (Frey, et al., 2006) is built for each driving cycle and for the entire group data as well. For example, Figure 8 represents a VSP distribution. In this example, around 14 percent of this trip has 0 *kW/t* of VSP and 6 percent has +1 *kW/t* of VSP.

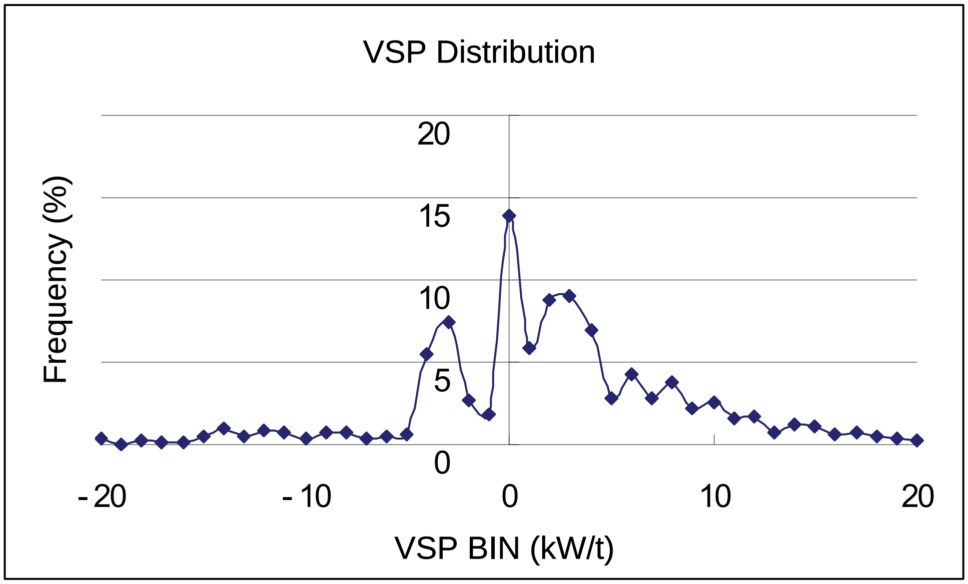


Figure 8 Example of VSP Distribution

4.4.3 Significance of Using VSP as Key Evaluation Factor

The answer is that VSP can better reflect emission characteristics. VSP explains how different driving conditions of automobiles affect emissions by taking a physical view. Generally speaking, speed and acceleration are considered to affect emissions considerably. Nevertheless, how close the relationships between speed/acceleration and emission are is questionable. Why is VSP chosen to evaluate driving cycles instead of other commonly used parameters, such as speed, acceleration? The reason is that VSP captures most of the dependence of light-duty vehicle emissions. The dependence of CO, HC, and NOx emissions on VSP is closer than on several other commonly used parameters. In order to uncover these points, a sensitivity analysis is conducted to compare the relationships between the emission and speed, acceleration and VSP based on test data collected from a principal arterial roadway. The sensitivity analysis calculates the squared correlation coefficients between emission and speed, acceleration and VSP respectively. **Error! Reference source not found.**, Figure 10, and Figure 11 show these correlations. From **Error! Reference source not found.**, the lower speed (0 – 70 km/h) has a kind of linear correlation particularly with NOx and CO2, however, there are clearly vibrations when speeds are high (higher than 70 km/h). Moreover, speed does not have such good correlations with HC and CO as with NOx and CO2. Figure 10 illustrates scattered points in which no clear correlations between acceleration and various emissions are present. Figure 11 shows the correlations between VSP and these emissions. Although there are negative and positive acceleration (negative acceleration is deceleration) and VSP, it does not mean the engine generates negative output. Therefore, all series of points are analyzed without reference to their being either negative or positive.

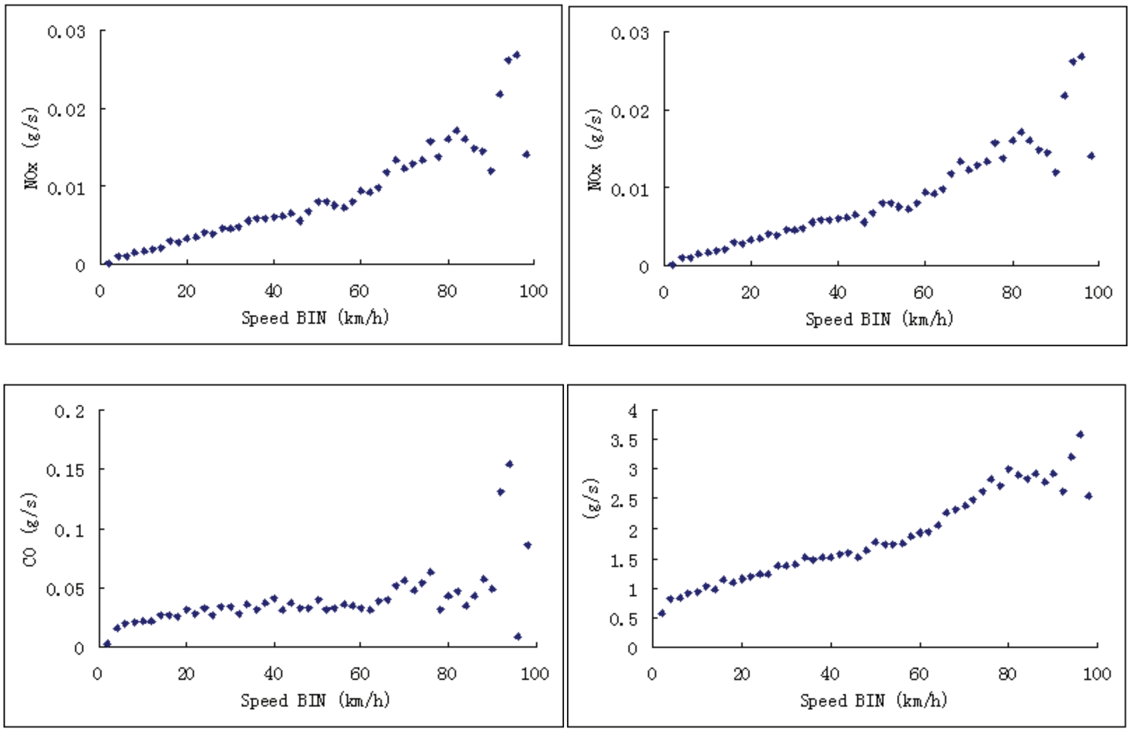


Figure 9 Correlations between Emissions and Speed

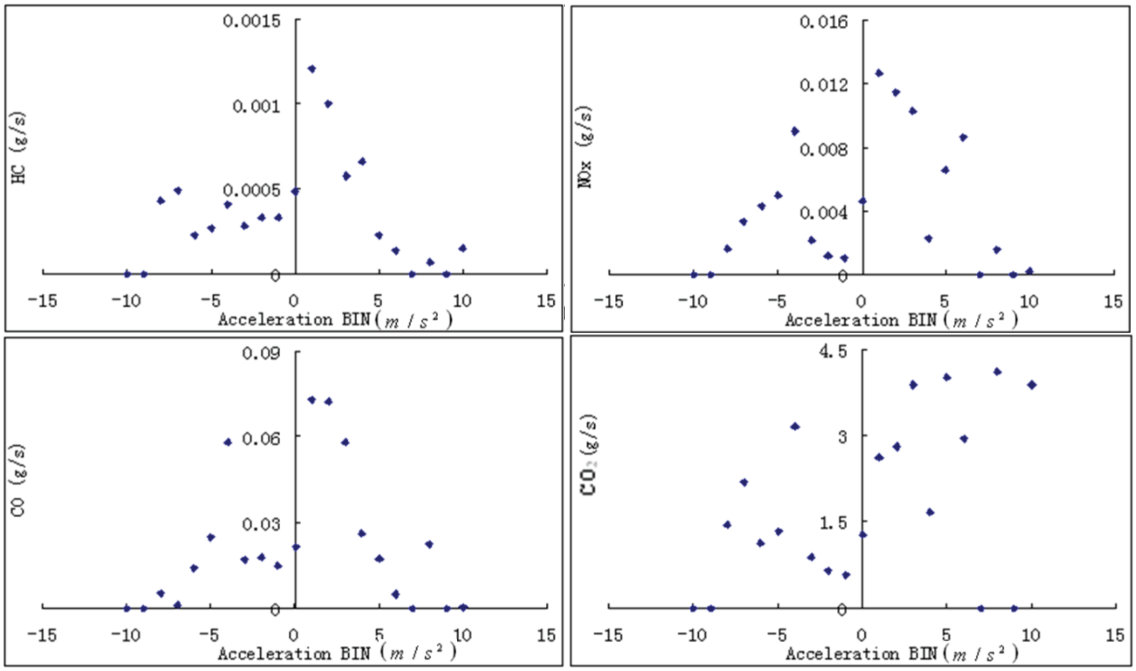


Figure 10 Correlations between Emissions and Acceleration

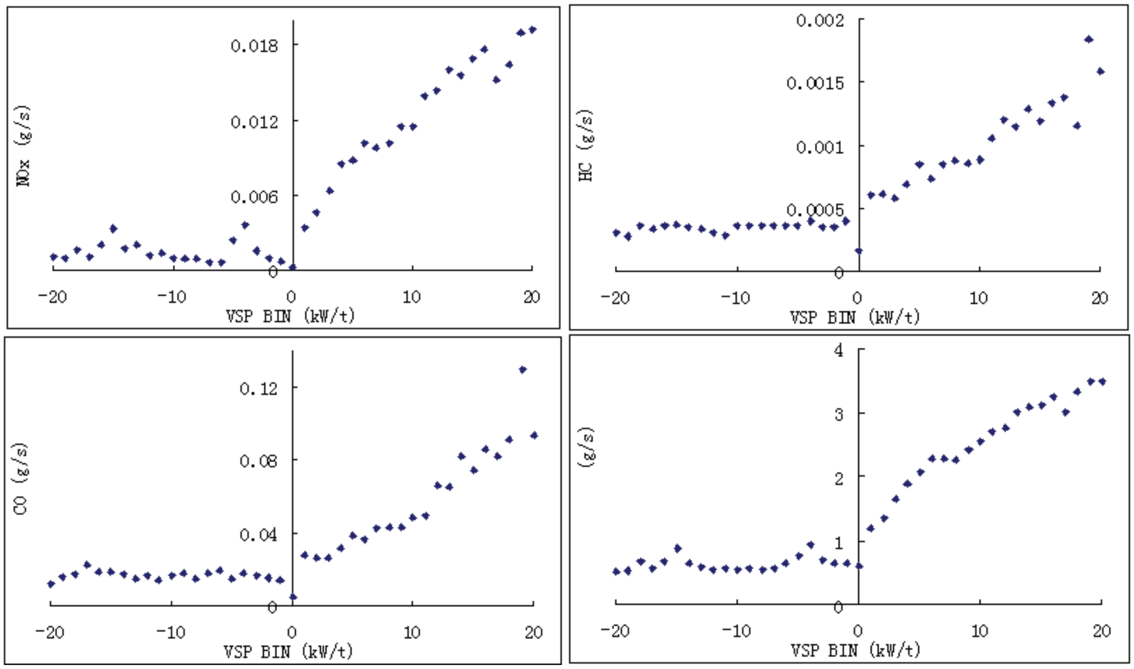


Figure 11 Correlations between Emissions and VSP Distribution

Since subjective judgments for observing the trend of points are biased and not accurate, a curve-fitting technique is applied to analyze relationships between each pair of relevant variables. Table 3 lists the squared correlation coefficients for these relationships. From these results, it is observed that the acceleration has the least direct correlation with emissions. The speed has good relationship with CO2, and a fairly good correlation with NOx, whereas the speed does not have good relationships with HC and CO. In addition, the high speed does not have the good relationships as does the lower speed. From Table 3 it is shown that VSP has more comprehensive correlations with all such emissions in both the low and high speed ranges.

Table 3 Squared Correlation Coefficients for Sensitivity Analysis

	Squared Correlation Coefficients with			
	NOx	HC	**CO**	**CO_2**
Speed (km/h)	0.8854	0.4379	0.3948	0.9457
Acceleration ($m \cdot s^{-2}$)	0.3676	0.4194	0.4304	0.2156
VSP (kW/t)	0.9408	0.9422	0.9391	0.9458

From what has been discussed above, the following conclusions can be made:

1. VSP can be easily obtained particularly for LDGV. As long as the speed and acceleration are available, VSP can be calculated.

2. VSP explains the emissions when the vehicle is operating in the physical perspective, whereas relationships between speed/acceleration and emissions are built on statistical analysis. Moreover, **Error! Reference source not found.**, Figure 10, and Figure 11 show that the speed and acceleration have less comprehensive relationships with emissions than does VSP.

3. VSP includes a range of information on driving conditions, such as idling and cruising.

4.4.4 Mean Root Squared Error

In order to further explore the significance of VSP, Figure 12 is created to show a comparison between the VSP distribution for the driving cycles and the VSP distribution for the entire group data using the freeway/expressway test data as an example. This illustration is similar in concept to the work reported by Frey, et al. (Frey, et al., 2006). If two distributions are more similar, in principle, the two curves are much closer.

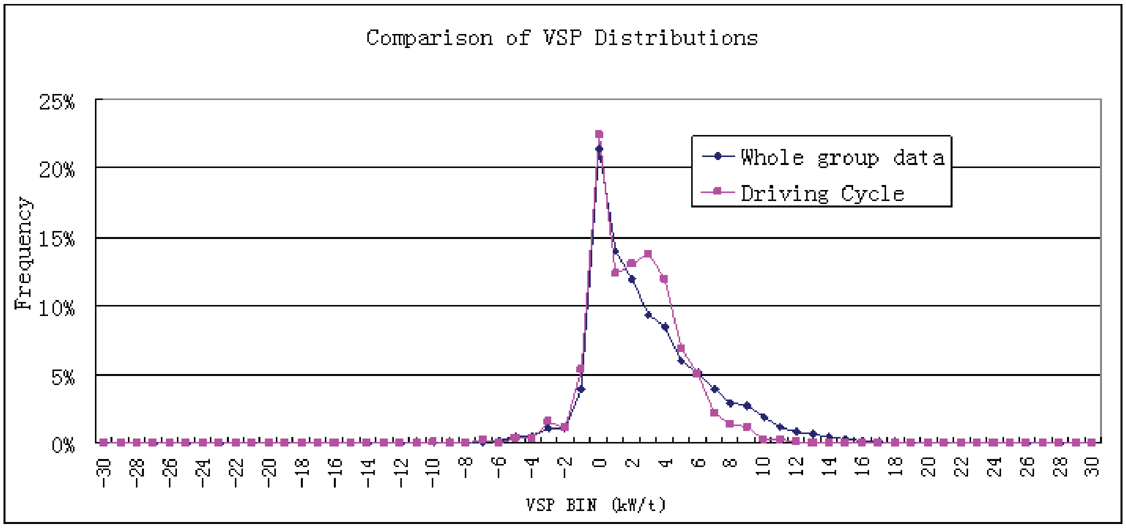


Figure 12 VSP Distributions of the Driving Cycle and Whole Freeway/Expressway Data

In the interest of quantification for the difference between two VSP distributions, the Mean Root Squared Error (MRSE) of VSP distribution is used to estimate the difference. It is calculated by Equation (7) and selected as the indicator for evaluating driving cycles.

$$MRSE = \sqrt{\frac{\sum_{i=-30}^{30}\left(bin_i - bin_{i\,cyc}\right)^2}{61}} \tag{7}$$

where: bin_i is the value of *ith* bin for the whole group data and bin_{icyc} is the value of *ith* bin for the candidate driving cycle.

Based on the above discussion, Figure 13 illustrates the procedure of the proposed approach in evaluating driving cycles. On the one hand, a VSP distribution is calculated based on the whole group data. On the other hand, after the candidate driving cycle is developed, the corresponding VSP distribution of the candidate driving cycle is calculated. And then, MRSE can be calculated according to these two VSP distributions.

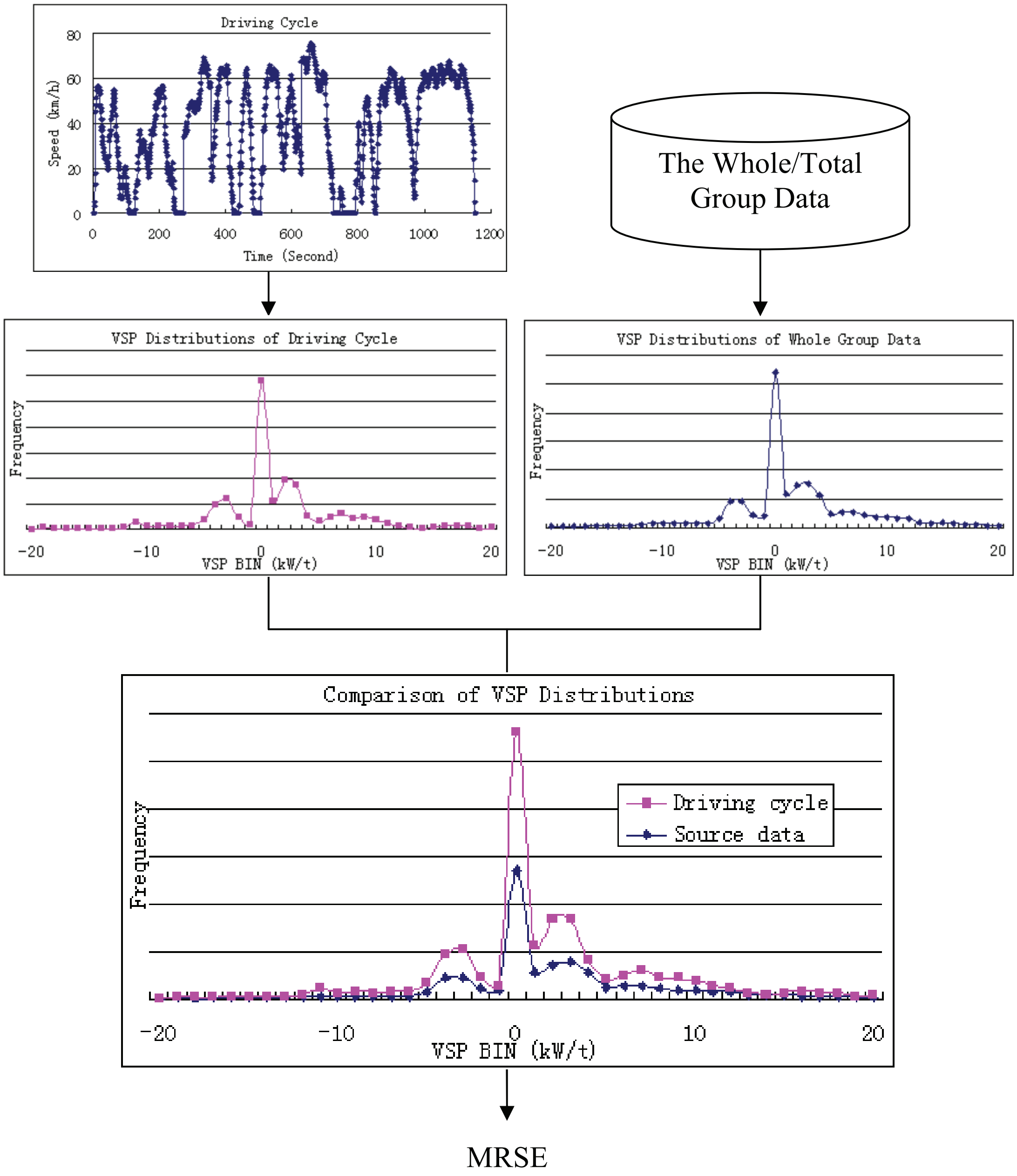


Figure 13 Procedure for the Evaluation of Driving Cycles

4.5 Determination of Final Driving Cycles

As shown in Table 2, candidate driving cycles were pre-selected based on the Ni in Equation (4) with five pairs of weights. Table 4 shows the MRSEs of the VSP distributions of the candidate driving cycles based on Equation (7). The numbers in the table are MRSE values. The candidate driving cycle with the least MRSE is selected as the final driving cycle for a specific facility. Table 4 indicates that those driving cycles that have less MRSEs for the VSP distributions also have less activity differences except for local streets, however, VSP is not simply equal to the speed profile. The final driving cycle does not need to have the least activity difference with the whole source data, because of the fact that similar driving activity does not at all times result in similar emission according to previous analysis. In the end, four final driving cycles representing four facility types are determined based on Table 4. Figure 14 shows four speed-time traces of selected driving cycles for four facility types. Further, **Error! Reference source not found.**, shows some key activity measures of these four driving cycles to help explain the speed profile of these driving cycles. These parameters have the same definitions as those in Step 3 of the "Proposed Methodology for Developing Driving Cycles" section.

Table 4 MRSEs of VSP Distribution of Candidate Driving Cycles

Facility Type	***(1:0)***	***(0.69:0.31)***	***(0.5:0.5)***	***(0.31:0.69)***	***(0:1)***
Local Streets	0.0047	0.0037	0.0038	0.0038	0.0066
Minor Arterial	0.0105	0.0105	0.0121	0.0121	0.0166
Principal Arterial	0.0059	0.0064	0.0064	0.0064	0.0139
Freeway/Expressway	0.0081	0.0081	0.0081	0.0086	0.0146

Note: (1:0), (0.69:0.31), (0.5:0.5), (0.31:0.69), and (0:1) are weight pairs.

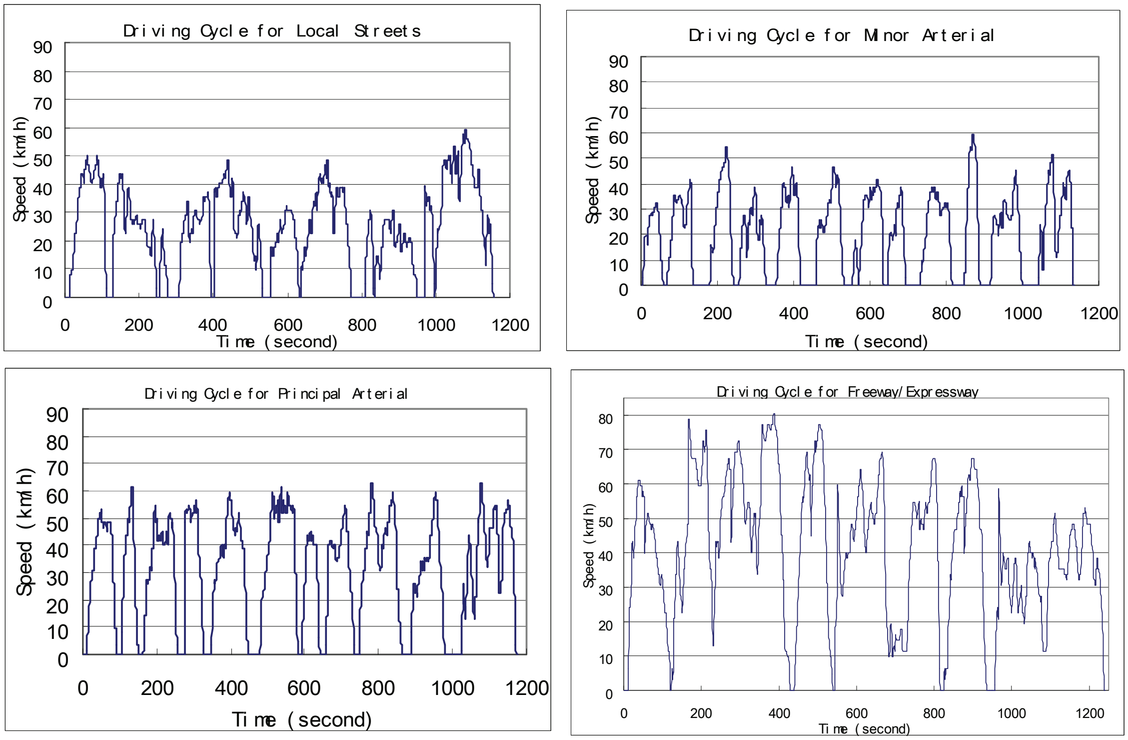


Figure 14 Driving Cycles for Four Facility Types

Table 5 Parameters of Final Driving Cycles

	Local Streets	**Minor Arterial**	**Principal Arterial**	**Freeway/Expressway**
Pi (%)	23.2%	37.3%	26.4%	9.4%
Pa (%)	22.5%	22.2%	24.3%	27.9%
Pc (%)	31.3%	21.1%	24.0%	35.5%
Pd (%)	23.0%	19.4%	25.3%	27.2%
V_1 (km/h)	21.90	17.22	27.63	39.14
V_2 (km/h)	29.01	28.13	38.20	43.51
Max. Speed (km/h)	59.54	59.14	62.84	80.55
Aa ($m \cdot s^{-2}$)	0.58	0.69	0.72	0.67
Ad ($m \cdot s^{-2}$)	-0.68	-0.83	-0.75	-0.72
Numbers of microtrips	9	12	11	6
NO_x (g/km)	0.2921	0.4863	0.5487	0.4632
HC (g/km)	0.0872	0.0888	0.057	0.0514
CO (g/km)	2.9676	3.0022	3.0014	2.0963
CO_2 (g/km)	151.78	186.50	141.29	125.15

4.6 Development of Driving Cycles for Evaluation and Comparison

With the explanations and presentations provided in earlier sections, the methodology about the development and evaluation of driving cycles was presented. The proposed methodology was applied to the available data to develop driving cycles which represent real world driving conditions better than those of the existing methodologies. In order to demonstrate that the proposed methodology will achieve better driving cycles in practice, a different set of driving cycles are developed based on the same data source, but by using the existing methodology which only considers driving activity measures.

As a result, two sets of driving cycles are developed in this study. One set of driving cycles is the product of the proposed methodology in this study as presented earlier and another one is developed by the existing methodology which only considers activity factors. First, a set of driving cycles is developed using the steps in the proposed methodology in the previous section. Then, another set of driving cycles is developed by only considering vehicle activity measures. In this case, when the candidate microtrip pool is being developed, all candidate microtrips for each facility type are ranked using only the activity part of *ComboDiff*, and then the evaluation process is applied to this additional set of driving cycles to determine the final driving cycles.

Figure 15 provides an example to demonstrate the procedure to compare two sets of driving cycles for the principal arterial. The same procedure is applied to the data source of each facility type.

In the "Criteria of Selection" for micriotrips in Figure 15, there are two types of criteria to be used in developing the driving cycles: one is based on *ComboDiffI*; and another is based on the activity part of *ComboDiff*. Different criteria will result in different candidate driving cycles. After candidate driving cycles are developed, the proposed evaluation method will be applied to every candidate driving cycle in both sets, and then corresponding MRSE values are calculated. The final driving cycles for each set of driving cycles will be determined according to MRSE values. Further, the comparison of MRSE between two different sets of driving cycles will show which set is better.

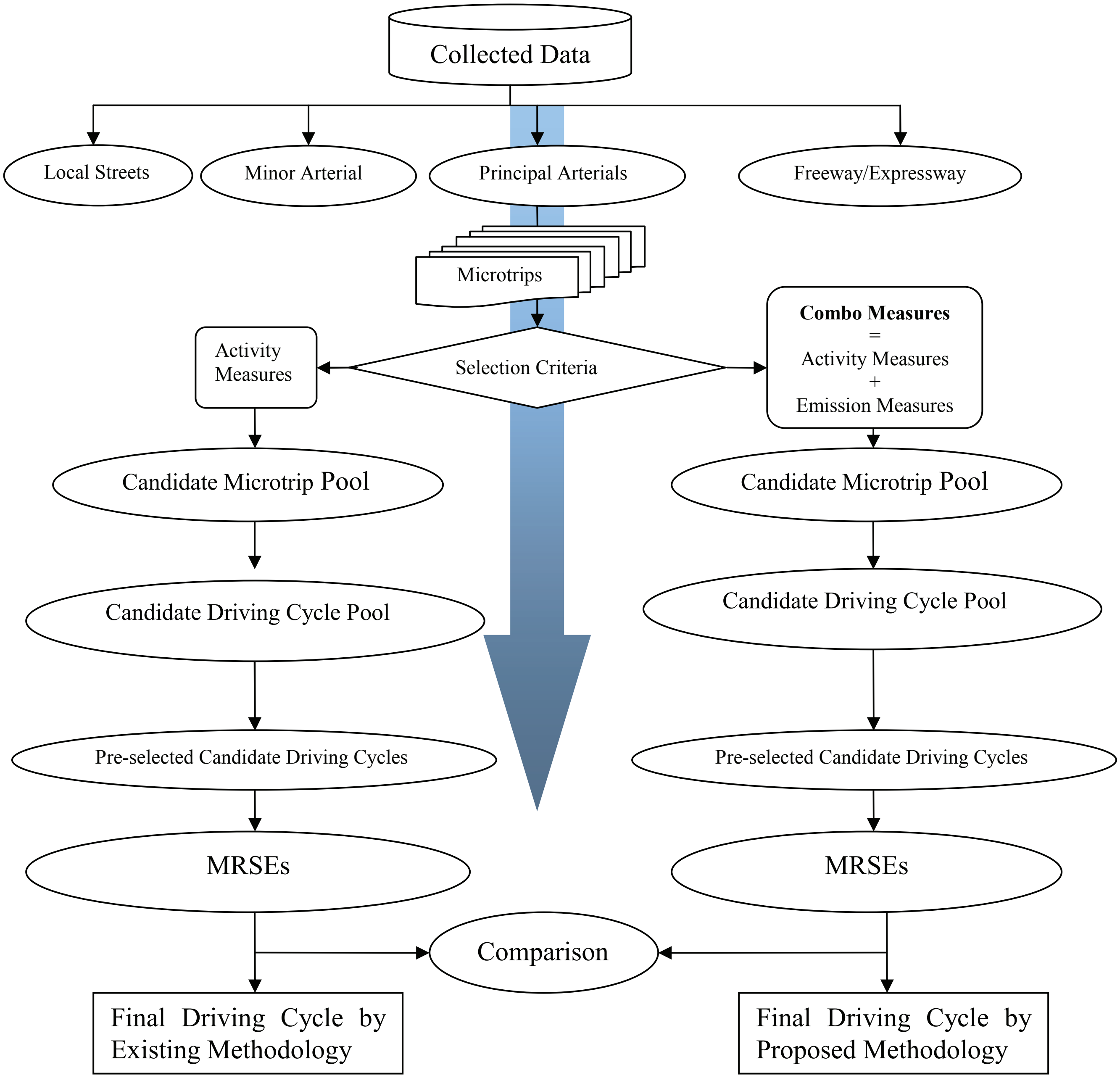


Figure 15 Flowchart of Methodology for Development of Driving Cycles

4.7 Comparison between Different Driving Cycles

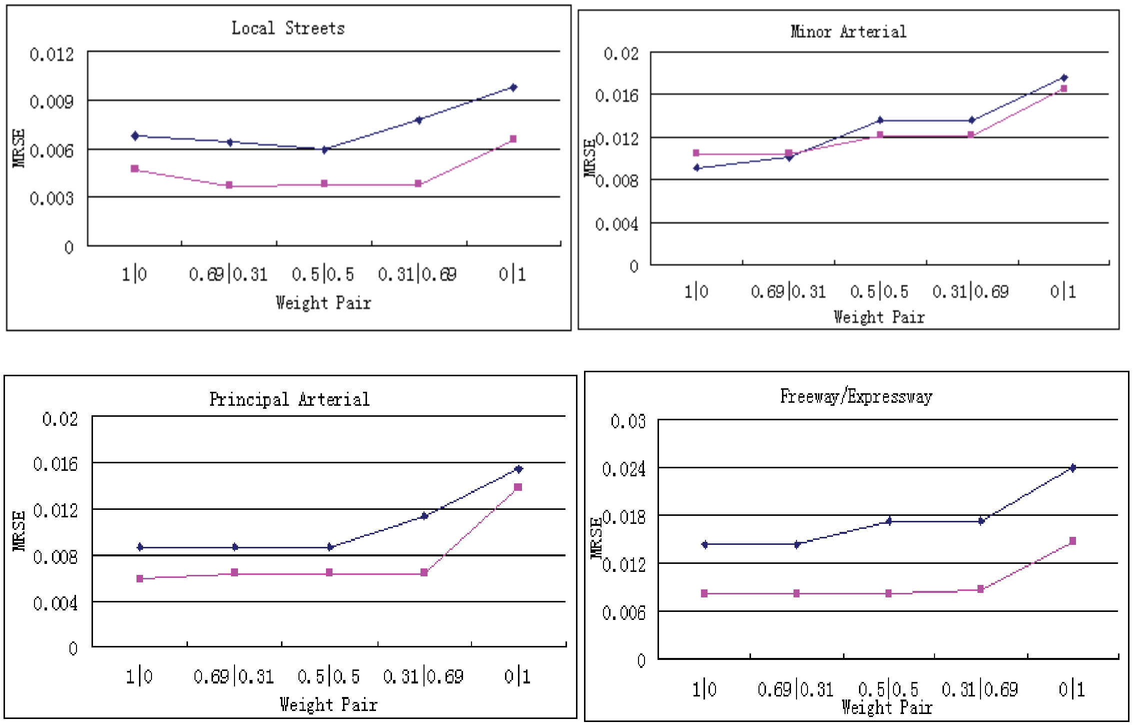
As stated earlier, existing driving cycles have only attempted to represent or reflect the speed profile of real world driving. This research has attempted to develop driving cycles that represent the features of driving activities as well as emission characteristics.

Table 6 provides the results of the comparison between two sets of driving cycles described in the previous section.

Table 6 Comparisons between MRSEs of Two Sets of Driving Cycles

Facility Types	**POOL**	**1|0**	**0.69|0.31**	**0.5|0.5**	**0.31|0.69**	**0|1**
Local Streets	**Activity only**	0.0068	0.0064	0.0060	0.0078	0.0098
	ComboDiff	0.0047	0.0037	0.0038	0.0038	0.0066
Minor Arterial	**Activity only**	0.0091	0.0101	0.0136	0.0136	0.0175
	ComboDiff	0.0105	0.0105	0.0121	0.0121	0.0166
Principal Arterial	**Activity only**	0.0086	0.0086	0.0086	0.0114	0.0155
	ComboDiff	0.0059	0.0064	0.0064	0.0064	0.0139
Freeway/ Expressway	**Activity only**	0.0144	0.0144	0.0172	0.0172	0.0240
	ComboDiff	0.0081	0.0081	0.0081	0.0086	0.0146

Figure 16 illustrates the results of Table 5 by graphs. It is shown in Figure 16 that MRSEs of the driving cycles developed, based on the proposed methodology in this research, are consistently less than those of the driving cycles developed based on only the activity part of *ComboDiff* no matter what weight pair was utilized during the procedure of development except for two cases of minor arterial.



Note: —◆— *Existing Driving Cycles;* —■— *New Driving Cycles.*

Figure 16 Comparisons between MRSEs of VSP Distributions of Two Kinds of Driving Cycles

These results indicate that more representative driving cycles can be achieved by synthesizing those microtrips that are similar to the sample data in both activities and emissions characteristics. Therefore, emission factors do matter in the development of driving cycles and should be incorporated in the development of driving cycles.

4.8 Application of Driving Cycles

One of the major applications of driving cycles is emission estimation. The emission factor is an important measurement of a vehicle's emission levels. Because the data collected in Beijing is used as the data source and IVE model is specifically designed for obtaining the emission factors in the cities in developing countries, this model is chosen to estimate the emission factors based on the driving cycles developed in this research. An analysis of the IVE model indicates that the driving pattern is a main input parameter for the model and it profoundly affects the estimated result.

On the other hand, emission factors can also be derived from the field test data. In the data source, every test record includes corresponding emission information. Emission factors can be calculated by accumulated emissions divided by accumulated kilometers traveled. Further, emission factors derived from field test data are considered as an objective measure which is able to reflect the driving situation as well as emission conditions in the real world. A comparison, between the emission factors estimated using the IVE model and the emission factors derived from field test data, shows the level of accuracy of emission estimation. Except for the variable input of driving pattern, every other input parameter to the IVE model is the same; the accuracy of emission estimation is able to indicate the accuracy of driving cycles which compose the input parameter of driving pattern to IVE model. This is another way to assess the quality of driving cycles. Accordingly, the two sets of driving cycles developed in earlier sections are applied to the IVE model respectively to project emission factors in order to show the different levels of accuracy of the emission estimations as well as driving cycles.

4.8.1 Emission Factors

Emission factors are used to provide the estimates of air pollutants or greenhouse gas emissions based on the amount of fuel combusted and the distances the vehicles traveled (or similar activity data). Emission factors can be presented in the following units: gram/kilometer, gram/mile or gram/kilogram (of fuel consumed). An emission factor can be defined as the average emission rate of a given pollutant for an individual driving vehicle, relative to the intensity of a specific activity. Different types of vehicles with different pollutants have different emission factors. Emission factors directly represent the level of the vehicle's emissions, which are the basis and foundation of research on the design of control strategies for emissions.

4.8.2 Significance of Using IVE Model

As mentioned in Chapter 2, there are a number of widely accepted emission models, such as MOBILE6, EMFAC and COPERT. MOBILE6 is an emission factor model for predicting criteria emissions as well as CO_2, and toxics from cars, trucks, and motorcycles under various conditions in United States.

The EMFAC model was developed by the CARB and used to calculate emission rates from on-road motor vehicles from light-duty passenger vehicles to heavy-duty trucks that operate on highways, freeways, and local roads exclusively in California.

At present, the COPERT III model is the most commonly used model in Europe for official national inventories of emissions from road traffic. COPERT III is a MS Windows software program which was developed as a European tool for the calculation of emissions from the road transport sector. The emissions calculated include regulated and unregulated pollutants such as Nitrous Oxide (N2O), ammonia (NH3) and Sulfur Dioxide (SO2), and the fuel consumption is also computed (Kouridis, et al., 2000).

However, the above models cannot take into account the differing technologies and conditions that exist in most of the developing countries. Most existing models do not include the full range of global warming and local toxic emissions that are needed to fully evaluate the impact of motor vehicles on the environment. Most importantly, these models do not include the flexibility of inputs that accommodate different driving patterns. The IVE Model is specifically designed to have the flexibility needed by developing nations in their efforts to address on-road source air emissions.

4.8.3 IVE Model

The University of California at Riverside, College of Engineering—Center for CE-CERT developed the IVE model in 2004, with the support of the Global Sustainable Systems Research (GSSR), the International Sustainable Systems Research Center (ISSRC) and the EPA (Nicole, et al., 2004). The model predicts local air pollutants, greenhouse gas emissions, and toxic pollutants. It is specifically designed to have the flexibility needed by developing countries in their efforts to address mobile source air emissions, and it has been applied in several cities worldwide including Mexico City, Mexico (Davis, 2004), Nairobi, Kenya (GSSR, 2002), Pune, India (GSSR, 2004a), and Beijing (Liu, 2007) & Shanghai (Cheng, 2007), China. The advantage of the IVE model is that it takes into account the differing technologies and conditions that exist in most developing countries and vehicle driving patterns, such as VSP and engine stress distributions which have a profound effect on the tailpipe emissions of vehicles.

The IVE model is applied in this study to generate travel-based model emission factors for major air pollutants and CO_2 using driving cycles as an important input parameter. These modeled emission factors are compared to the emission factors obtained from OEM-2100.

4.8.4 Emission Estimation Process in IVE Model

The driving pattern is one of most important components in IVE model and the driving cycle is the abstract and description of the driving pattern.

The emission estimation process in the IVE model multiplies the base emission rate for each technology by each of the correction factors, which is defined for each vehicle technology, and the amount of vehicle travel for each technology to arrive at a total amount of emissions produced. The emission estimation of the IVE model begins with a base emission rate and then applies a series of correction factors to estimate the amount of pollutions from a variety of vehicle types.

The correction factors can be categorized as Local Variables (ambient temperature, ambient humidity, etc.), Fuel Quality Variables (gasoline overall, gasoline sulfur, etc.) and Power & Driving Variables (driving pattern, air conditioner usage, etc.).

The final step multiplies these results by the ratio of the average speed of the LA4 driving cycle and the average speed of the modeled cycle and further multiplies this by the distance traveled (for running emissions). The EPA Urban Dynamometer Driving Schedule (UDDS) is commonly called the "LA4" or "the city test" and represents city driving conditions. It is used for light duty vehicle testing. The LA4 was derived from an actual driving route through Los Angeles (LA) that was selected to represent a typical city driving pattern.

Among various input parameters to the IVE model, only that driving pattern which belongs to Power & Driving Variables is adjusted according to driving cycles developed in this study; other correction factors are default values which are set according to previous works during the development of IVE model.

4.8.5 Execution of IVE Model

The user required input data for the IVE model are built upon two input files: the Fleet file and the Location file. The Fleet file accommodates up to 300 technology/age classes which include the technology/age of the test vehicles employed in the field tests. Data inputs to the Fleet file include vehicles driving in each technology group and vehicles equipped with an air conditioning unit. The Location file provides information on a specific location for one or more times during the day. In addition, an important input into the location file is the driving behavior which includes the amount of driving and the driving patterns (speed and acceleration profile).

In the IVE model, driving patterns are characterized using two parameters:

- Vehicle Specific Power (VSP), and
- Engine Stress.

Both of the above parameters are obtained from the general knowledge of the vehicle type and a second-by-second speed trace. More detailed information about the equations to calculate VSP and Engine Stress as inputs into the IVE model can be obtained from the IVE user manual (GSSR, 2004c). The two sets of driving cycles developed in previous sections are respectively applied to the IVE model as driving behavior parameters.

Regarding other inputs, light duty vehicles consisting of medium or small size gasoline passenger cars are selected. Furthermore, multiple fuel injections (3-way) are chosen to tailor the emission projection. The VKT is not the research objective of this paper, so “Beijing PC fleet 2004” is chosen to describe driving distribution. “Beijing PC fleet 2004” is an option as one of the default parameters provided in IVE, which offers the VKT information of passenger cars in the year 2004 for Beijing. IVE classifies roads in Beijing into three groups: Residential, Arterial, and Highway. In this research, four types of driving cycles for four facilities (freeway/expressway, principal arterial, minor arterial and local streets) were designed. In the application of driving cycles, freeway/expressway, principal arterial and local streets are selected to apply to IVE model. The reason minor arterial is not selected is that there were bad traffic conditions in minor arterial during test which resulted in lower than typical average speed; in addition, minor arterial is similar to local streets in terms of travel speed and volume.

In the estimation of NOx, CO and CO_2 emission factors, IVE does not estimate HC but, instead, estimates volatile organic compounds (VOC) (Janssen, 1992). The conversion factor from HC emissions to VOC emissions is equal to 1.005 (Wu, et al., 1996).

In accordance with the above discussion, NOx, CO, CO_2 and VOC emission factors for the three road facilities (Residential, Arterial and Highway) are estimated by the IVE model based on the driving cycles developed in this study. On the other hand, the emission factors for these road facilities can also be calculated based on real world data.

Table 7 shows the comparison of the results. The number in the parenthesis shows the relative differences between estimation results and the real-world data. Generally, IVE model overestimates vehicle emissions when the data collected in Beijing is used. This is mainly because the foundation of IVE model is the existing emissions data in the US, Europe, Japan and a few other countries (GSSR, 2004b). Although ISSRC has done studies in various cities in the developing countries (Liu, 2007) to update the relevant base adjustment data for IVE model, the major focus is laid on fleet composition and vehicle technology distribution, instead of on the emission foundation.

Table 7 Comparison between IVE Estimation and the Tested Results

Facility Type	Emissions	Combo DC	Test Data
Residential	**NOx**	0.7403 (46.3%)	0.5065
	VOC	0.1704 (23.1%)	0.1384
	CO	3.6705 (5.7%)	3.8941
	CO_2	282.9714 (39.7%)	203.3972
Arterial	**NOx**	0.9097 (65.5%)	0.5496
	VOC	0.1677 (195.8%)	0.0567
	CO	4.9463 (114.2%)	2.3092
	CO_2	269.4486 (66.4%)	161.9229
Highway	**NOx**	0.7485 (37.9%)	0.5428
	VOC	0.1357 (45.6%)	0.0932
	CO	4.6195 (23.4%)	3.7445
	CO_2	212.0653 (19.5%)	177.442

Note: *1. Combo DC means driving cycles developed based on ComboDiff;*

2. Emission factors' units all in gram/km.

4.9 Summary

The data source is critical in this research. The data collection was elaborately performed using PEMS techniques, which provides a unique approach for collecting real-time emissions as well as driving activity data. The data collection was conducted by scholars and students at BJTU who then pre-processed the collected data to control the data quality. The processed data collected from LDGVs were selected as data source to develop the driving cycles for this research.

The methodology proposed in this research consists of six steps to develop candidate driving cycles for each particular facility type. The most significant improvement of this methodology is taking both driving activity measures and emission measures into account to develop driving cycles.

Since VSP can readily connect the driving modes with emissions and sensitivity analysis, it follows that VSP has more comprehensive correlations with NOx, HC, CO, and CO2 than the speed and the acceleration, and so a VSP-based method was proposed in order to evaluate the driving cycle and to select the final driving cycle among candidate ones.

A second set of driving cycles was developed to represent existing driving cycles. The foregoing analyses and results show that the driving cycles developed by the proposed methodology are able to better represent real world LDGV driving conditions particularly in terms of emission characteristics than existing driving cycles.

One of important applications of driving cycles is emission estimation. The IVE model was utilized in this study to project emission factors using developed driving cycles as an important input parameter.

CHAPTER 5: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary of the Study

This research provides a full-scale review of existing studies on driving cycles. Second-by-second emissions data (including NOx, HC, CO, and CO_2) and the vehicle's activity and positional information were utilized as the data source for the development of driving cycles. Previous studies have developed driving cycles to represent driving conditions, but they can not reflect vehicles' emission characteristics simultaneously. This research proposes a methodology that considers both driving activity measures and emission measures to develop driving cycles which could not only represent typical driving conditions, but also reflect corresponding emission characteristics for the LDGVs driving in the study area. Furthermore, an effective VSP-based evaluation method for driving cycles was proposed to fill a gap in the fieldwhich was used to select final driving cycles to represent different driving conditions for classified facility types. Two different sets of driving cycles were developed by the proposed methodology and existing methodology, respectively. The evaluation method was applied to the two sets of driving cycles. Results show the new driving cycles developed by the proposed methodology are able to better represent real world driving conditions. At last, the two sets of developed driving cycles were applied to an IVE model to estimate emission factors. The new driving cycle will project more accurate estimation results in terms of estimation by IVE model when emission factors derived from the field test data were considered as a standard.

5.2 Conclusions

In summarizing the review of current research on driving cycles and presenting the results from a comparison between the existing and those newly developed driving cycles, the study provides the following conclusions.

1. PEMS has proved to be a satisfactory technology for emission measurement. In the research on driving cycles the United States, Europe, and Japan started their studies relatively early

and have, therefore, made much progress in this field. However, there was the limitation of data collection either in method or in quantity when those driving cycles were being developed. PEMS, which was developed in recent years, is a new technology for studying transportation air quality. The foregoing analyses and results proved that PEMS offers advantages and benefits over and above those of traditional techniques. PEMS provides a unique approach for collecting real-time emissions as well as driving activity data—both of which are essential for the development of new generation driving cycles.

2. The proposed methodology for developing driving cycles is advanced. The existing methodology takes only driving activities measures into account. While the purpose of driving cycles is to estimate the emissions, it is insufficient and unreliable to consider only the emission measures in the procedure of the development of driving cycles. The methodology proposed in this study not only takes driving activity measures into consideration but also considers emission characteristics as additional measures to develop driving cycles. Such driving cycles are able to better represent driving conditions as well as emission characteristics in the real world.

3. VSP is promising in the field of on-road emission research. VSP can be easily obtained and includes information on driving conditions, such as idling and cruising. VSP explains emissions when the vehicle is operating in the physical perspective since VSP is the output power of engine of the vehicle. Furthermore, sensitivity analysis in this study indicates that the acceleration has little direct correlation to emissions, and that speed correlates with NO_x and CO_2 in the low speed range. VSP has, however, more comprehensive correlations with all four emissions in both the low and high speed range (Table 3).

4. The VSP-based evaluation of driving cycles is an advanced method. Traditionally, there has been a lack of an efficient and verifiable evaluation method to estimate the driving cycles in the field. In this research, VSP was utilized as an evaluation method for assessing driving cycles in terms of emission characteristics. Besides the similarity of the emission condition, the final driving cycles determined by the VSP-based evaluation method also record driving activity.

5. The new driving cycles developed by the proposed methodology properly reflect the different driving conditions under various types of facilities. In the case study, there was a relatively high proportion of idling on minor arterials because there were significant conflicts between vehicles, cyclists, and pedestrians which delayed driving. Furthermore, the most emissions were generated on minor arterials.

5.3 Recommendations

In light of the findings and conclusions, this report provides six recommendations for future studies in this research field.

1. This research focused on LDGV. However, different types of vehicles have significantly different driving characteristics. It is recommended that driving cycles for heavily duty vehicles are worthy to be developed. Furthermore, driving cycles for vehicles using other types of fuel, e.g. diesel, should also be developed.

2. Driving cycles are based upon the enrichment of tested data. The availability of more data means that more representative driving cycles could be constructed. Continuation of such tests is recommended. Furthermore, different study areas should be considered across borders, e.g. the city of Houston, TX, United States would be good candidate. Such information will allow for comparison of driving cycles between various study areas.

3. Fuel consumption is an important parameter for the emission estimation and control. It is recommended that the factor of fuel consumption be incorporated in development of driving cycles as another key control measure.

4. Urban planning intends to create transport energy conservation strategies. It is recommended that urban driving patterns and fuel consumption patterns be systematically linked with driving cycles which can then be used to estimate spatial differences in transport energy use per capita.

5. VSP has quite good and comprehensive correlations with various emissions. Since the purpose of driving cycles is for emission estimations, it is recommended that driving cycles be developed using VSP as key criteria instead of activity and emission measures.

6. VSP is a promising concept and is very useful. A VSP-based emission model will be very interesting and practical. This new emission model can be developed based on the existing emission database. This area deserves further study.

APPENDIX

APPENDIX A: ACRONYMS

ADC	Athens Driving Cycle
BJTU	Beijing Jiaotong University
CARB	California Air Resource Board
CMEM	Comprehensive Modal Emissions Model
CO	Carbon Monoxide
CO2	Carbon Dioxide
ECE	Economic Commission for Europe
EMFAC	the Emission Factors Model
EPA	Environmental Protection Agency
EUDC	Extra Urban Driving Cycle
FTP	Federal Test Procedure
GHG	Greenhouse Gas
GPS	Global Positioning System
GSSR	Global Sustainable Systems Research
HC	Hydrocarbon
HDDV	Heavy Duty Diesel Vehicles
HDGV	Heavy Duty Gasoline Vehicles
I/M	Inspection/Maintenance
ISSRC	International Sustainable Systems Research Center
ITS	Intelligent Transportation Systems
IV	Instrumented Vehicles
IVE	International Vehicle Emission
KMT	Vehicle Kilometers Traveled
LDGV	Light Duty Gasoline Vehicle
LOS	Levels Of Service

MEASURE	Mobile Emission Assessment System for Urban and Regional Evaluation
MOVES	Motor Vehicle Emission Simulator
mph	mile per hour
MRSE	Mean Root Squared Error
N_2O	Nitrous Oxide
NEDC	New European Driving Cycle
NEDC	New European Driving Cycle
NH3	Ammonia
NOx	Nitrogen Oxide
OBD	On-Board Diagnostic
PEMS	Portable Emissions Measurement System
PM	Particulate Matter
SAFD	Speed-Acceleration Frequency Distribution
SFTP	Supplement Federal Test Procedure
SO_2	Sulfur Dioxide
SQL	Structure Query Language
UC	Unified Cycle
UCC	Unified Correction Cycles
UDDS	Urban Dynamometer Driving Schedule
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compounds
VSP	Vehicle Specific Power

APPENDIX B: EMISSION DATABASE STRUCTURE

Fields	Meanings
DATELINE	Test date (yyyy-mm-dd)
TIME	Test time (hh:mm:ss)
SPEED	mph
ACCEL	Acceleration ($m \cdot s^{-2}$)
ENG_RPM	Revolutions Per Minute
MAP	Manifold Air Pressure (kPa)
IAT	Intake Air Temperature (degrees Celsius)
FUEL	Fuel Consumption (grams per second)
NOX	Nitrous Oxide rate (grams per second)
HC	Hydrocarbon rate (grams per second)
CO	Carbon Monoxide rate (grams per second)
CO2	Carbon Dioxide rate (grams per second)
PM	Particulate Matter rate (grams per second)
LON	Longitude [ddd] [mm.mmmm]
LAT	Latitude [ddd] [mm.mmmm]
ALT	Altitude
TYPE	Test type (OBD/Sensor Array)

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